Univerza *v Ljubljani*

Fakulteta *za gradbeništvo in geodezijo*

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ADVANCED CONSTRUCTION PROGRESS MANAGEMENT WITH BEXEL MANAGER

Napredno upravljanje spremljave napredka del z okoljem Bexel Manager

BIM A+ European Master in Building Information Modelling

Master thesis No.:

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Cosupervisor: Veljko Janjić

Ljubljana, 2022

Co-funded by the Erasmus+ Programme of the European Union

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BIBLIOGRAFSKO – DOKUMENTACIJSKA STRAN IN IZVLEČEK

UDK: **004.85:69-5(043.3)**

Avtor: **Iuri Gonçalves Rodrigues**

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Naslov: **Napredno upravljanje spremljave napredka del z okoljem Bexel Manager**

Tip dokumenta: **Magistrsko delo**

Obseg in oprema: **91 str., 81 sl, 1 pregl**

Ključne besede: **vodenje projektov, gradbena dela, strojno učenje, analiza EVA, spremljanje napredka**

Izvleček:

Številni mednarodni organi in zdrženja vidijo digitalizacijo gradbenega sektorja kot neizogibno in bistveno za napredek in trajnost arhitekturne, inženirske in gradbene industrije. Prednosti digtalizacije obsegajo od izboljšanja trenutnih praks do integracije prelomnih orodij in tehnologij, ki omogočajo nastanek novih in izboljšanih procesov. Proces spremljanja napredka gradnje je bistveni del gradbenih projektov, ki analizira in upravlja izvedbo del, kar je ključnega pomena pri preprečevanju prekoračitve rokov in stroškov ter na sploh za učinkovito izvedbo projektov.

Eden od glavnih vidikov učinkovitega projektnega vodenja, ki omogoča boljši proces odločanja, je zmožnost analiziranja neskladij v informacijah o izvedenem in načrtovanem napredku ter jih na jasen način skomunicirati z drugimi deležniki. Ta študija se osredotoča na raziskovanje avtomatizacije spremljane napredka gradnje z identifikacijo novih tehnologij in metod za pridobivanje in uporabo potrebnih informacij in kako obdelati te informacije za analizo prisluižene vrednosti EVA. Študija se osredotoča tudi na analizo zamud pri gradbenem projektu in analizo načinov, kako nadzorovati njegovo uspešnost in izkoriščanje prednosti integracije informacijskega modeliranja stavb (BIM), orodij in programske opreme za vodenje projektov.

Disertacija vključuje zasnovo ogrodja z uporabo BIM in programske opreme za vodenje projektov Bexel Manager za spremljanje napredka gradnje in gprimer uporabe, ki omogoča presojo glede na stroškovno in časovno uspešnost z uporabo ključnih kazalnikov (KPI).

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BIBLIOGRAPHIC– DOKUMENTALISTIC INFORMATION AND ABSTRACT

UDC: **004.85:69-5(043.3)**

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Title: **Advanced Construction Progress Management with BEXEL Manager**

Document type: **Master thesis**

Scope and tools: **91 p., 81 fig., 1 tab.**

Keywords: **Construction management, Construction works, Progress monitoring, Earned Value Analysis, Machine learning**

Abstract:

The digitalization of the construction sector is seen by several international organs and policy makers as inevitable and vital for the Architecture, Engineering and Construction Industry prosperity and sustainability. Its benefits span from the enhancement of current practices to the integration of disruptive tools and technologies allowing the emergence of new and improved processes. The progress management process is an essential part of the construction projects that analysis and manages the performance of works developed proving to be key in avoiding time and costs overrun, delivering projects efficiently.

One of the main aspects of efficient project management that enables an accurate process of decision making is the ability to analyse as-built and as-planned progress information discrepancies and communicate it in a clear way. This study focuses on exploring the automation of construction progress management by identifying new technologies and methods of retrieving and use information required, and how to process this information to analyse earned value and delays of the construction project in an ongoing manner, controlling its performance, and taking advantage of the integration of Building Information Modeling (BIM), project management tools and software.

The dissertation includes the design of a framework using BIM and the project management software *Bexel Manager* to manage the construction progress and applies it to a use-case scenario to ultimately assess it in terms of costs and times performance through key performance indicators (KPI).

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ACKNOWLEDGEMENTS

At the conclusion of this academic stage, I would like to thank all those who have accompanied and support me on this journey. I would also like to express my gratitude to the BIM A+ course organization for giving me the opportunity to participate and achieve my goals in this field of studies.

To my supervisor, Tomo Cerovšek, I want to thank for the trust, advice and all the support given throughout the development of this dissertation. His sharing of knowledge was of the utmost importance and value which I am truly grateful for. I would also like to convey my appreciation to Mr. Veljko Janjić and Bexel Consulting for the availability and assistance, and also for providing resources for the development of the case study.

To my lifelong friends and family, I want to thank for being part I thank for being part of my journey of personal and professional growth in both good and bad moments. To my girlfriend, her support during this time was vital in overcoming difficulties and challenges, helping me reach another milestone. I am deeply grateful.

I am also extremely grateful for the support, companionship, and encouragement from the friends I made during this academic journey.

Lastly, I want to express my deepest gratitude and appreciation for their friendship, values transmitted, and the support given during all my life.

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1 INTRODUCTION

1.1 BIM in the Construction Sector

The construction industry, which embodies real estate, infrastructure, and industrial structures, is one of the most important in the world economy. According to a McKinsey study [1] the sector accounts for 13% of the global GDP. Together with its larger ecosystem it forms the backbone of global economies and are essential to society's day to day lives. From breathtaking cityscapes and expansive infrastructure to sustained innovation, construction is responsible for a wide range of impressive accomplishments.

However, the sector has consistently done poorly in several areas for a long time, suffering from low margins and high risks. The Institute of Chartered Accountants in England and Wales (ICAEW), a globally recognised accounting and finance professional organization, states that the construction sector is "fragile" where even the largest companies can find themselves just a few contracts away from falling into debt, therefore the industry needs to build a stronger foundation moving forward [2]. Among others, several difficulties within the sector are related to labour shortages, competitiveness, resource and energy efficiency, and productivity. The last-mentioned lagging behind global productivity by more than 30%. If the construction productivity matched the global average productivity, it would be possible to finance half of the total infrastructure demand [3]. One of the reasons for the stagnant productivity in this field is lack of automation during the construction phase. The integration of new technologies has been scattered and the acceptance of disruptive business procedures within design and construction has been gradual and restrained mainly to larger companies [4] .

According to the European Construction Sector Observatory, the digitalisation of the construction sector is growingly acknowledged as a major game changer for the industry. For instance, the Boston Consulting Group predicted that full-scale digitalization in non-residential construction would lead to yearly global savings of €0.7 to €1.2 trillion (13 to 21%) in the engineering and construction phases alone [5]. Thus, in Europe for example, the European Commission (hereafter referred to as EC) has supported, promoted, and established several policies and initiatives (such as the EU BIM Task Group and the EU Digital Construction platform) aiming to foster the digitalization of the construction industry by promoting and integrating the use of Building Information Modeling (hereafter BIM) within construction projects in the EU directive on Public Procurement [6].

"Digital services are making all our lives simpler, faster and more connected. In most cases, this manifests itself into our everyday activities becoming more efficient. This same paradigm is now beginning to be realised in the construction sector where Building Information Modelling (BIM) is helping our industry to be more innovative, become more technologically advanced and create and care for our built assets and infrastructure." [7]

Early research on the advantages of BIM by Stanford University's Center for Integrated Facilities Engineering (CIFE) examined data from 32 noteworthy projects and revealed that BIM implantation led to: a decrease in non-budgeted changes of up to 40%; time reduction to cost estimation preparation of 80%; saving of contract value of up to 10% through early clash detection; a reduction in whole project costs of up to 7%. Such results support the growing body of research with regard to BIM enabling contractors to prevent the additional costs related to rework during an asset construction [8].

However, as the construction sector is one of the least digitised sectors of the economy. Apart from Building Information Modeling (BIM), a scarce number of digital technologies have seen wider adoption. As recently noted in a European Commission (EC) report, the digitalisation goes beyond the sole use of BIM and involves data acquisition, process automation and other technologies connected to digital information and analysis [6]. McKinsey considers that technological progress and emerging disruptions, such as digitalisation of products, design and processes, will trigger industry overhaul [1].

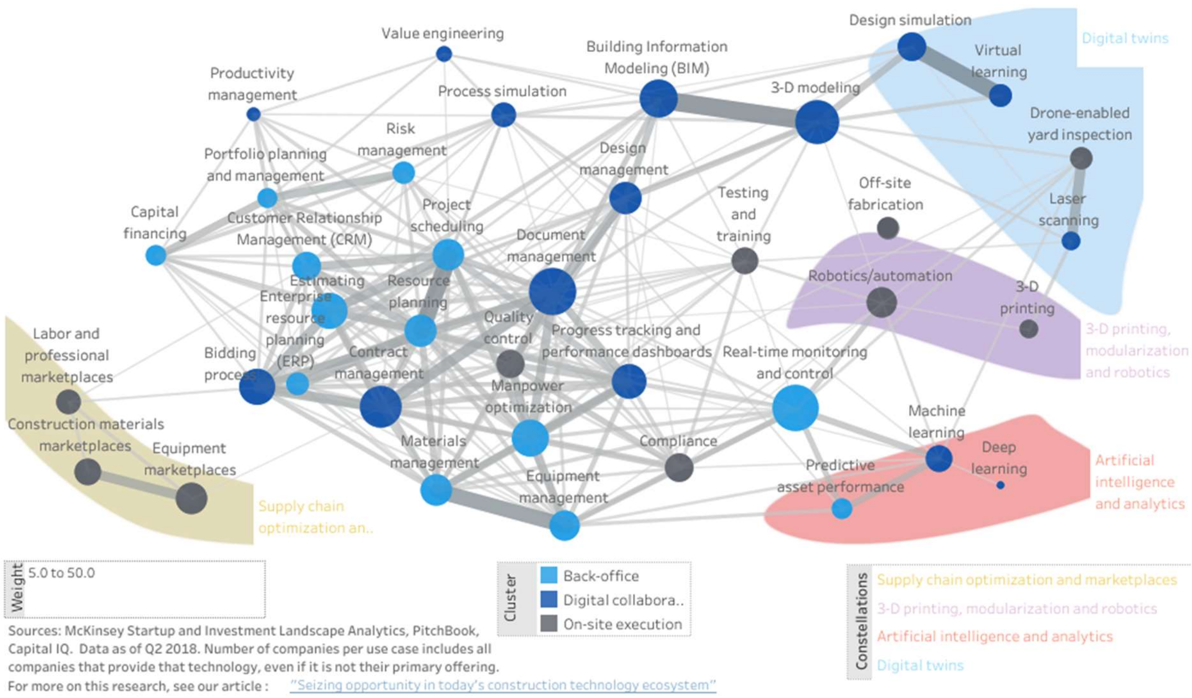

Figure 1 - Construction emerging technologies ecosystem by McKinsey [9]

One can agree that the adoption of emerging technologies will increase the efficiency of construction project management and improve productivity. Successful projects are defined as the achievement of the proposed objectives within time and budget, meeting the quality output standards at the desired level of performance and technology, while using the allocated resources in effective and efficient way, fulfilling the requirements of customers and stakeholders. Therefore, cost and time control are fundamental key aspects to construction project management attained by continuous progress monitoring, assessment of different plans and information, and appropriate decision making to achieve the baseline objectives of each project [10].

1.2 Problem Statement and Objectives

Digital technologies are driving better collaboration and a shift towards more data-driven decision-making, essential in an era where projects are ever more complex and larger in scale. In turn, companies are adopting 5D Building Information Modeling advanced analytics and full-scale project management solutions by considering the addition of cost and dynamic scheduling to the spatial design parameters in 3D.

However, management of construction progress and preparation of dynamic plans using BIM along with selected suppliers and subcontractors, changes of technical details, work sequencing and progress deviation may be very challenging tasks for all involved key stakeholders in the construction. Traditional approaches for progress management require manual data entry and manipulation which time-consuming, and prone to human error, increasing project's cost overruns and delays.

Delays are arguably the cause of numerous recurrent disputes and claims that lead to litigation. It occurs in most construction projects and their significance is dependent on the size of the project [11].

The aim of this study is to provide accurate digital representation of the state of construction in terms of time-quantity-costs and quality for an effective Construction Progress Management (CPM), to deliver projects efficiently, on time, and on budget. Special focus will be given to:

- Research on the progress management framework, from the process of innovative data acquisition and entry methods for construction progress monitoring to earned value analysis and progress KPIs.
- How to optimize the organization of the models, breakdown structures, internal organization of models into groups, assemblies, and model metadata classifications.
- Study of delay analysis with Bexel Manager software workflows.

1.3 Key Research Questions

The following research questions will outline the thesis structure:

- How to select the appropriate data acquisition technology and method based on the project characteristics?
- What are the requirements of point clouds for an efficient progress monitoring and delay analysis?
- How to optimally organize the models, including WBS, organisation in groups, attached model metadata classifications at different granularities?
- How to process progress management information and communicate it between stakeholders?

1.4 Hypothesis

The hypotheses of this study are:

- The leverage of field data acquisition and AEC digital technologies enhances the automated progress management.
- Accurate generation of As-Built and As-Planned 4D models enable the speed and improvement of delay and earned value analysis of construction projects.

1.5 Research Workflow

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- In the first chapter the dissertation topic is put into context through the introduction of important concepts and state of the integration of BIM in construction. Additionally, the dissertation problem and objectives are stated, along with key research questions, hypothesis and the structure of the thesis.

Chapter 2: LITERATURE REVIEW

- The second chapter develops the research on the state of the art of the topics related to the advanced construction progress management methods. In a first section, construction progress management contractual requirements, methodology workflow and software applications research are described. The following sections comprise data acquisition methods and technologies identification and analysis, information requirements for data acquired processing, dynamic scheduling concepts, progress monitoring outputs and analysis, and finally insight on the software used in this study, *Bexel Manager*.

Chapter 3: FRAMEWORK

- This third chapter describes the proposed framework for construction progress management. The workflow is detailed and entails progress entries, collaboration process between involved parties, information validation, progress assessment and information management, and communication of the results to the stakeholders.

Chapter 4: CASE STUDY

- Here a case study is demonstrated through the application of the framework proposed during the construction phase, and since it is not based on a real case scenario, some assumptions based on construction knowledge were made.

Chapter 5: CONCLUSIONS

- At last, discussion and conclusions are developed through analysis and overview of the different processes, stating positive aspects and also some limitations. Moreover, the chapter also gives a summary and contributions of the study, and finally recommendations for future research.

Methodology

To accomplish the current dissertation goals and objectives, the methodology below will be followed for the development of this study.

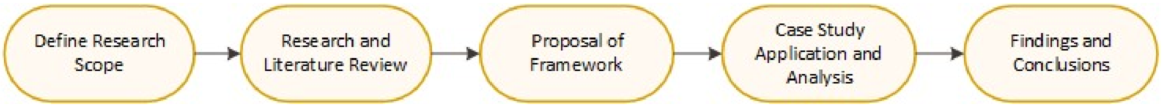


Figure 2 - Research methodology process.

2 LITERATURE REVIEW

2.1 Construction Progress Management

Construction projects are information intensive. Access to accurate information in a timely manner is essential for making good decisions and ensuring a project is completed on time and to specification. Good quality documentation makes it easy for contractors to carry out the work required in an effective way, with reduced difficulties and delays. Although a lack of productivity in construction due to inaccurate and erroneous information and documentation has been observed, which ultimately has led to schedule and cost overruns, and disputes. Targeting the improvement of management and monitoring processes during the construction phase of a project can help to improve cost, time and quality control, the three basic and most important performance indicators in construction projects [12], [13].

Construction project management is defined by Walker in [14] as:

“The planning, co-ordination, and control of a project from conception to completion (including commissioning) on behalf of a client, requiring the identification of the client’s objectives in terms of utility, function, quality, time and cost; the establishment of relationships between resources; integrating, monitoring and controlling the contributors to the project and their output; and evaluating and selecting alternatives in pursuit of the client’s satisfaction with the project outcome.”

Given that the nature and functions of each component are similar, BIM capabilities on construction projects align with the Project Management knowledge domains. As a result, BIM can be seen as a powerful and effective project management tool in the construction sector, enhancing aspects such as integration, collaboration, communication, documentation, cost and time management, and so forth. Ultimately, BIM has the capacity to be the catalyst for project management process reengineering to improve the integration between the different stakeholders involved in innovative construction projects [15].

Construction progress management is the core link of project management, playing a vital role in the construction management performance. As mentioned earlier, one of the key aspects of efficient project management that enables prompt corrective decision making is the capacity to portray as-built and as-planned progress divergences and communicate progress information clearly. Currently, traditional methods to assess and report progress, such as visual inspections, manual data collection and data entry, extensive data extraction from documentation, and textual progress reports are still employed. Site managers, for example, typically spend considerable amount of time surveying, documenting, and examining the progress of the works [16]. These methods are error prone, sparse and take away time and focus from managers for the task of decision-making. Besides, they poorly communicate the progress of the project, which in combination with the aforementioned aspects leads to delays and cost overruns. The main challenges for project managers to control construction progress in a traditional manner are summarized below [17]:

- Labour intensive and time-consuming – the current methods for collecting construction data require extensive manual work and require extracting data from various sources that are not always completely independent.
- Low quality of manually collected and extracted progress data – Collecting progress information manually by staff on site, depends on the status seen on site and the information gathered, which can be subjective and not always reflect the impact of site conditions on construction.
- Non-systematic and generic methods of progress measurement - Without a detailed comparison examination of the project schedule, resources, and cost data, incorrect assumptions and misleading progress quantities can be created. Errors may include overpaying and failing to account for anticipated delays.
- Progress monitoring reporting is visually challenging – There is a high complexity in portraying and communicating variable information (schedule, cost, and performance) in a comprehensive way and simultaneously portray the complex spatial and visual characteristics of both as-built and planned construction.

To overcome these issues and manage construction projects efficiently, systematic and innovative comprehensive methodologies for progress monitoring require further development. This will allow progress variations between as-planned and as-built to be monitored and reported to the project management as soon and regularly as possible, supporting and enhancing routine decision-making and consequently allowing savings of the overall project cost and duration.

Progress management is intrinsically linked to time and cost control of the project, occupying a specific position on the project life cycle.

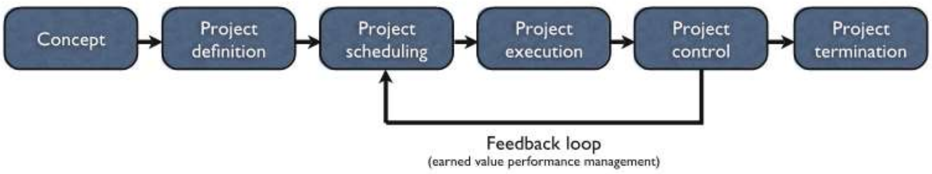


Figure 3 - Project Life Cycle and earned value performance management loop [18]

Monitoring the state of project operations and activities, such as updating project progress and managing changes to the baseline schedule to meet the plan, relies on the process of controlling time and durations. Cost control is the process of managing deviations from the cost baseline and updating project costs while overseeing and analysing its performance. This makes it possible to identify deviations from the plan and take remedial action to reduce risks. [18]. Both processes are depicted below through the data flow diagram, which represents the inputs, tools and techniques and outputs:

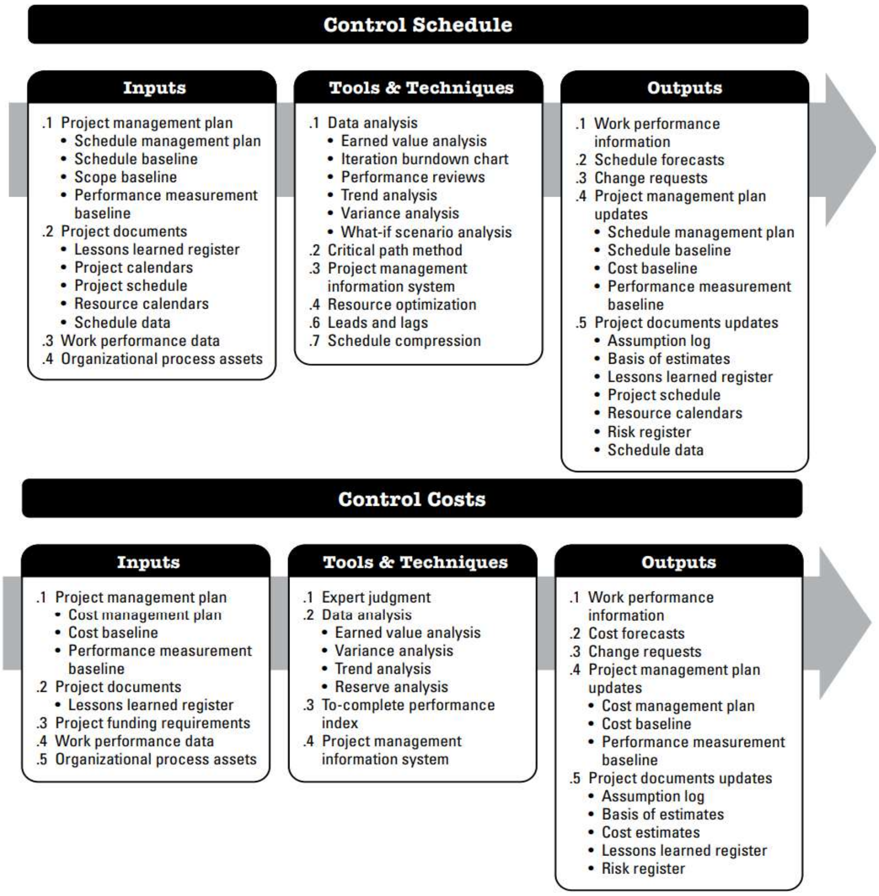


Figure 4 - Time and cost control data flow (inputs, tools and techniques, and outputs) [18]

With the advancement and extensive application of information technology in the construction sector, BIM launches new possibilities for construction progress management. By integrating all relevant information of a certain project, BIM technology improves progress management by leveraging more accurate and faster processes used for construction simulation, engineering measurement, materials procurement, visualisation of as-built construction elements, contract management and quality assurance. It also helps to establish the construction baseline schedule prior to the start of works, shaping and creating the basis for the dynamic process of project progress and simulation. After all the preliminary work for the construction phase is completed, using BIM software tools to assist the construction phase from the beginning until the end of the project, supports durations tracking of each activity and forecasting of the whole project, as well as keeping records of all construction phase including as-built models. Ultimately, BIM technology plays an important role in enhancing efficiency, ensuring quality, saving costs and reducing time frames, assisting the progress of the construction dynamic management process. [19]

2.1.1 Contractual Requirements

The successful implementation and execution of BIM projects builds upon the crucial pre-condition of legally binding agreements which address model uses, qualities, contents, and workflows, especially taking into account the handover of the project assets model to the owner. Moreover, applied terminology and global responsibilities are defined in general contract specifications (generally presented in the contract appendix). In this context, the Employer's Information Requirements (EIR) and the BIM Execution Plan (BEP) are both essential documents forming part of the contractual agreements, that are developed specifically for each construction project. Defined by the client in the EIR, and further developed in the BEP, the most significant aspects for construction progress management are as follows:

- BIM application targets in the project and how the digital processes shall be undertaken.
- Roles and responsibilities detailed specifications.
- Specify handover dates and procedures, such as BIM-based cost analysis at monthly valuation meetings or updated schedules for construction.
- Data exchange formats and compatible software applications. Using open data standards, such as the Industry Foundation Classes (IFC), are critical to avoid overwork and interoperability issues, preserving the simple flow of information between participants.
- Level of Information Need (LOIN) for each element type including detailed lists of attributes of the models to be delivered.
- Establishment of a Common Data Environment (CDE), for a proper documentation of the project, management of information, keeping track of changes and progress, enhancing collaboration.
- Survey strategy, such as the use of point clouds or light detecting and ranging (LiDAR).

In the pre-award BEP, potential contractors (bidders) describe their strategy to meet the EIR requirements. After the contract is awarded, the BEP is further developed and detailed into its final version [20]. The following points are essential for a clear definition of the information requirements, and help the understanding of the development of the current framework:

- **What?** The goal is to develop a framework for advanced construction progress management, using digital methods and technologies for data acquisition, dynamic scheduling, and Building Information Model, enabling more efficient delay and earned value analysis.
- **Why?** As explained earlier, there is a need to overcome issues related for example with time-consuming and error prone activities, such as manual data collection and treatment, or generic progress measurement. The latter can lead to loss of control over costs as well as productivity.

- **How?** Defining a methodology for the progress management workflow, from data gathering to internal organization of models into groups and model metadata classifications, including analysing pre-construction requirements to develop an efficient progress management during construction. The section 2.1.3 covers in detail the methodology workflow during the construction phase.
    - Prior to the start of works, it is essential to define the intended BIM Model use cases in the early stages of the project, as well as the LOIN. It provides a key starting point for the BIM project execution driving an appropriate As-Planned model development for construction by all involved parties. Since the focus is managing construction and its progress, according to BIM Excellence initiative (BIMe) [21], some of the main BIM model uses are identified accordingly: Construction Planning, Value Analysis, Quantity Take-Off, Cost Estimation. Also, prior to construction, a well-established CDE should be in place, to enable the documentation management during construction phase keeping track of any process updates and outcomes (i.e., As-Built BIM models, design changes to As-Planned models, real time analytics and dashboards, KPIs, project schedules and budget variances, progress-related documents such as reports or payment certificates) [22].
- **Who?** One of challenges for using BIM on construction projects is the legal and procedural challenges relative to standard and legal definition for BIM professional responsibilities [23]. BIM introduces several new tasks and responsibilities specially in management and coordination of digital building models. The BIM Manager plays a strategic role in the company and on each project, becoming accountable for the shift towards digital practices and for developing guidelines and standards involving workflows, model contents and best procedures for progress management during construction. He provides the work ground for the project manager to manage and monitor the progress of the project during the construction phase. Surveyors and site managers are held responsible for data acquisition on site that will be essential to support and enable the progress tracking.

2.1.2 Pre-Construction Baseline Planning

Construction projects' time and cost planning are intimately related tasks that are essential for successfully completing the project in the building process. Time planning is vital and has a significant impact on cost planning since its increase is proportional to the magnitude of the project's delays. The person in charge of estimating costs frequently collaborates with designers and decides expenses in connection to the stage of development or the project during the preliminary estimate. A BIM approach makes this even more tangible with the specific regulations on information management processes, such as the ISO 19650, by establishing a shared and collaborative environment through which, progressively with the design development, it becomes feasible to extract quantitative information directly from the created model for construction, in order to acquire a result in terms of costs (budget) for the project's execution. Thus, planning the project budget entails determining costs in advance, establishing the cash flow trend, and planning the necessary financial resources in advance to cover costs for labour, materials, equipment, etc [24].

By using models in an interoperable format, the 4D and 5D BIM approaches are critical to facilitate and complete the planning phase (Figure 5). The computations resulting from these approaches depend on the parametric modelling and subsequently quantity take-off, unit costs and the linkage of individual elements of the BIM model with the corresponding activities of the construction schedule. These activities and their execution durations are organized according to the work breakdown structure (WBS).

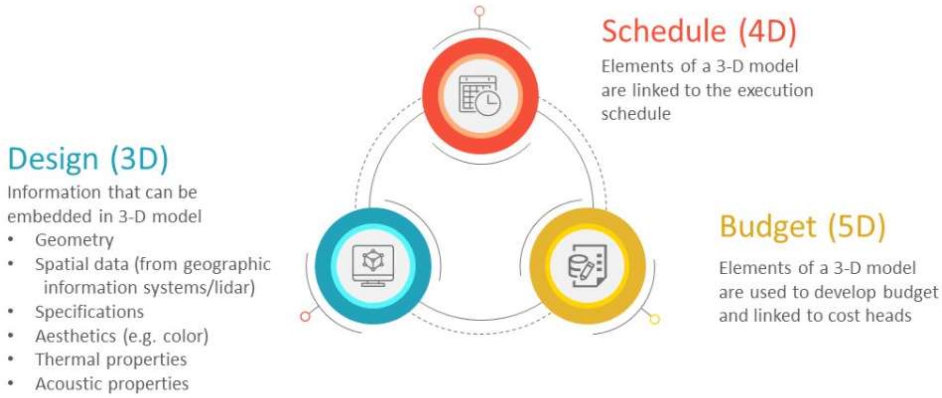


Figure 5 - Three main dimensions for construction progress management [25]

The establishment of WBS is a key step for organizing any project. It proves crucial within the project management planning processes, dividing the project into stages and work packages and enabling a clear definition of the scope of the project. The activities are usually defined under work packages instead being related to the individual elements. On the structure, a work package can encompass several building elements, and on another side the construction of these building elements, can englobe different work packages (reinforcement can encompass different concrete column elements, and the construction of a column element require reinforcement, formwork, concrete pouring and finishing work packages) [16]. Furthermore, the WBS definition positively impacts processes such as activities definition, and planning and control of the project schedule, and cost. Each model element is assigned a specific WBS code in a process of linkage, that represents its processing stage and activity regarding the construction work schedule. It may also be assigned items of the cost breakdown structure (CBS) (CBS is WBS in terms of cost implementation). The distinction between the elements will result in a better management of design, estimation, and construction [18], [26].

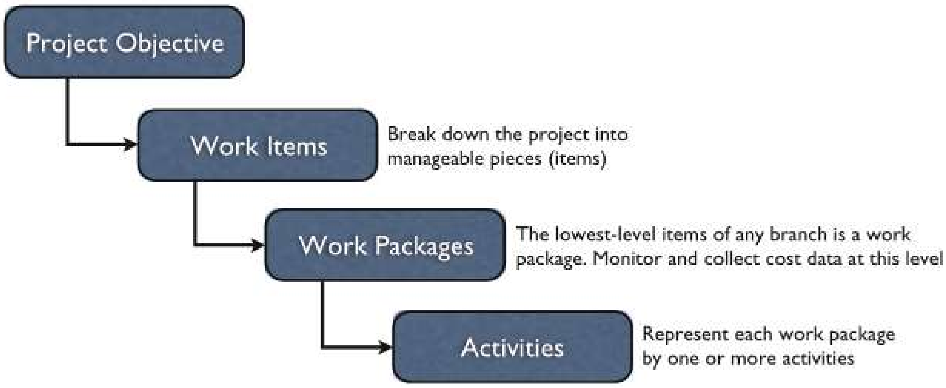


Figure 6 - Level of Work Breakdown Structure from [27]

The interrelation and linkage between the model elements, schedule information and cost, create a perfect scenario for the automation of cash flow analysis. When compared with the time-consuming traditional method, this approach is more efficient, taking advantage of the integration of quantity take-off (QTO), scheduling, and cost estimation [28].

In addition, the budget of a project needs to be created in a way that makes it possible to anticipate every type of cost and structure as well as to implement a simplified scheme of intersection between WBS and CBS. Figure 7 shows the typical WBS/CBS relationship matrix that links the breakdown of the project in its individual activities, with the costs structure related to each of these activities. Through an optimal deconstruction of the work in activities, the allocation of the relative costs is facilitated, and the estimator plans the budget for each work package and subsequently for the whole project.

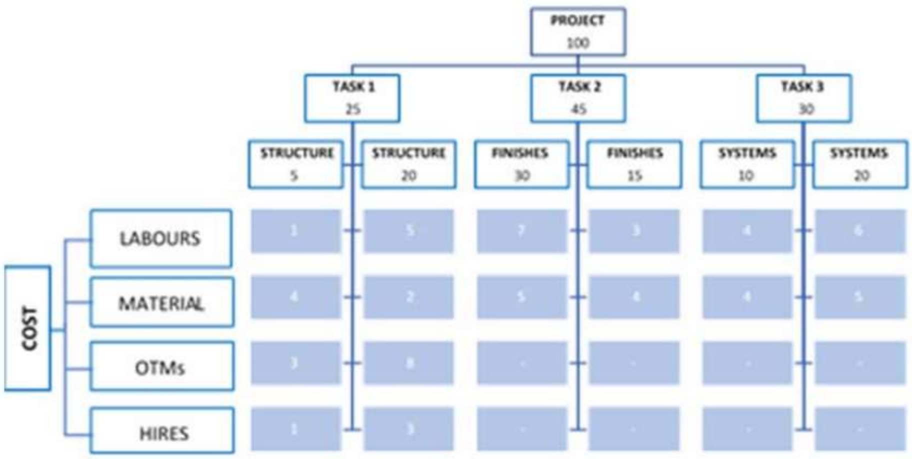


Figure 7 - Example of relationship WBS-CBS in activities within projects [24]

Finally, the activities durations together with their relative costs accumulated over time, provide the S-curve representing the planned value during the whole construction project, that serves as the baseline for the site budget (Figure 8). This process is crucial for the management of time and cost during the execution phase.

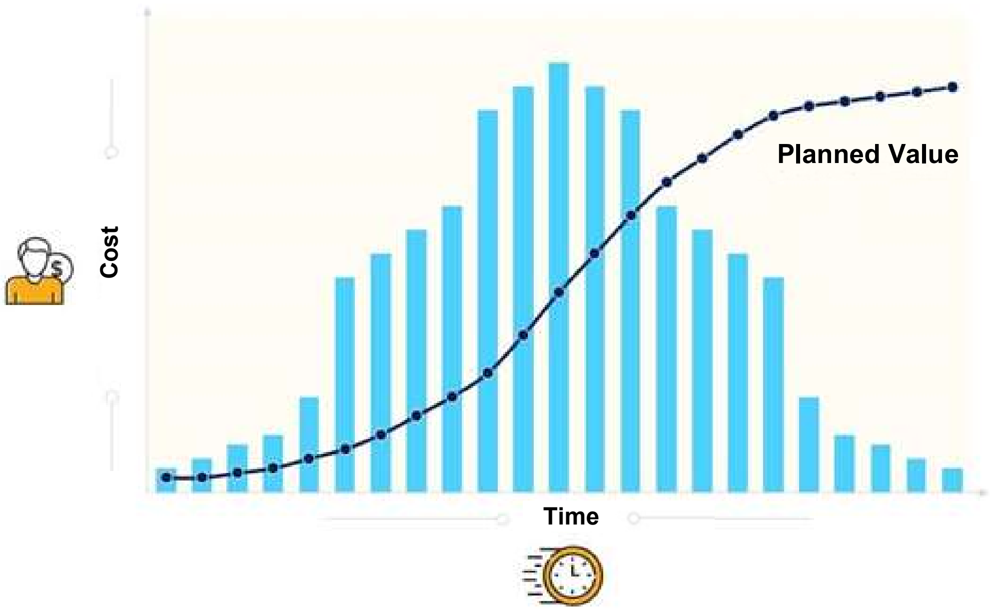


Figure 8 - Baseline Panned Value S-Curve [29].

Moreover, the synchronization of design and construction planning, through the connection of the construction plan to the BIM elements and enriching the model with construction equipment objects (scaffolding, shoring, cranes, etc.) allows the simulation of the construction process. Showing how the development of the works on site would look like at any given time, provides great insight into how the asset will be built day by day, revealing causes of potential problems and also opportunities for possible improvements (site, manpower, equipment, space conflicts, safety problems, etc.), while assisting adjustments to the work sequence and construction scheduling [4].

Finally, the required pre-construction process outcome for the progress management workflow is an as-planned digital model (integrating BIM models from the different disciplines, baseline construction schedule, and cost estimation), together with a pre-defined plan for progress monitoring on site, including monitoring scopes and data acquisition strategies [30].

2.1.3 Methodology Workflow

According to the Project Management Body of Knowledge (PMBOK) monitoring and controlling the a construction project "consists of those processes required to track, review, and orchestrate the progress and performance of a project; identify any areas in which changes to the plan are required; and initiate the corresponding changes" [18]. Automating the process of construction progress monitoring can enable an effective management and control of the projects. As mentioned earlier, it is crucial for reducing cost and schedule overruns, improving quality control, documentation, and communication.

Monitoring the performance and progress, is considered one of the major challenges for a construction project manager, due to the complexity and interdependency of activities and information collection from site. In fact, it represents a key factor for projects to be successfully delivered on time and within budget [16], [31]. The methodology for an innovative and accurate progress management relying on new technologies in the fields of data acquisition, and computer vision (CV) can be found below:

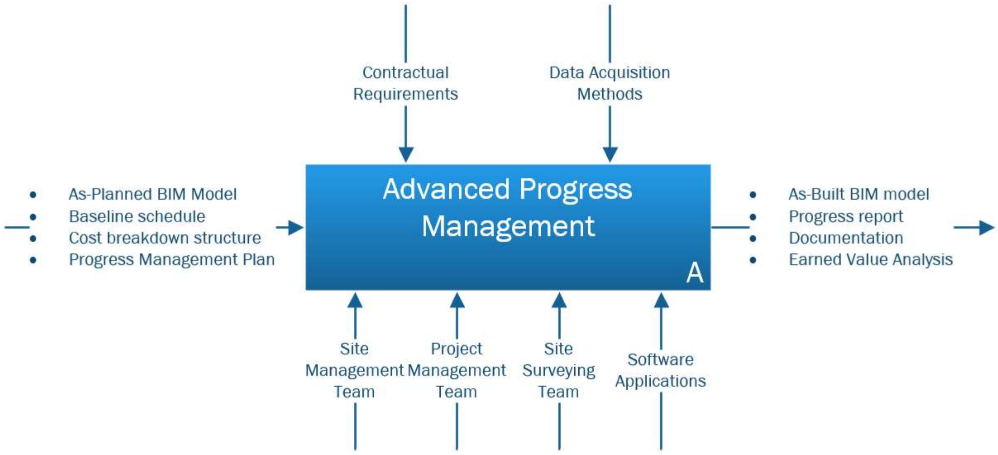


Figure 9 - General IDEF0 for Construction Progress Management.

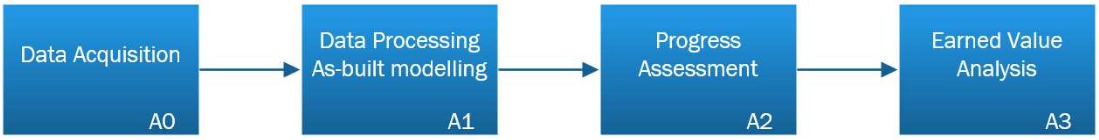


Figure 10 - Workflow for the Construction Progress Management.

The progress management process must be done throughout the construction phase period on a consistent basis. The Figure 10 represents a simple workflow of this process that happens recursively as construction on site progresses. Each of the sub-processes will be broke down and described on the next sections. Starting by data acquisition, the focus will be on overviewing different technologies, referring to methods, and plans for gathering visual data from works in progress on site. For documentation and progress tracking, it is crucial to address the processing of acquired data. From raw data towards as-built model development methods, different automated approaches and requirements are explored, illustrating the processing of initial data for the comparison between as-built and as-planned. Once the as-built model of the works developed on site at a certain moment is settled, it is possible to proceed to the comparison with the as-planned model and define the progress in terms of quantity of work completed and on-going vs what was planned for that period, referring also to dynamic scheduling control and management of works and resources. Finally, having the progress assessment for a certain time frame related to costs, the research targets the analysis of delays and earned value, exploring different KPIs and progress visualization to better communicate the project status with all the stakeholders, providing an effective ground and information for an efficient decision-making.

An early study by Zhang et al. [16], reflected on the need to create an automated process for progress management to improve the accuracy and real-time as-built information to overcome traditional methods. They developed and proposed a system to determine the progress of construction applied to the superstructure of buildings, using digital images captured on site, and evaluated its performance through workshops involving professionals such as project managers, planners, and quantity surveyors. Despite some difficulties, the results were positive and promising, showing great value in schedule and cost control through the constant monitoring progress process and alerts in advance regarding possible delays. Additionally, since then, automation in construction progress management has become even more consistent and accurate, driven by the exponential growth of technology, particularly in the area of artificial intelligence (AI).

As mentioned, one of the main topics that enables the practicality of this framework is the field of computer vision. Falling into the broad field of artificial intelligence, it is an interdisciplinary scientific field that uses computers capacity to obtain a detailed insight of visual data [32]. It allows computers to obtain numerical information from digital images, videos, depth images and 3D point clouds, process and analyse the information, and take action. One can say that computer vision is intrinsically connected to automation. Boosting automation on construction sites means leveraging better approaches to measure progress performance in the most cost-effective way possible, making computer vision a vital tool for innovation as some early studies have shown [33]. Recent research continues to support these approaches. Reja et al. [34] have developed an integrated process framework for Computer-Vision-Based Construction Progress Monitoring (CVCPM), discussing different arrangements of input-process-output options for each of the different stages of the framework proposing guidelines to structure these combinations showing the potential of CV in impacting progress management providing real-time, accurate, reliable information to project managers. Another extensive research by Xu et al. [32] investigated the potential to utilise computer vision for assisting construction management tasks, targeting the several fields related to progress monitoring including data acquisition, data processing and support for strategic decision making.

All computer vision methods start with visual data acquisition [32]. Currently, low-cost memory, affordable cameras with high resolution, and expanding bandwidth capacity have made it possible to capture and share photos of construction projects on an incredibly large scale. Not only the construction management team, but also contractors, owners, and subcontractors take photos of everyday works and project's development on site. There is a massive number of images collected throughout a construction project that could be more useful for management tasks [35]. The availability of such diverse and vast set of visual records representing the dynamic construction process captured at minimal cost, can enable the generation of as-built models at high definition. Acknowledging the aforementioned, Golparvar-Fard et al., in [36], proposed an automated approach to track, analyse and visualize construction progress based on unordered daily construction photographic collections and 4D IFC-based BIM models (deviations are automatically color-coded over the BIM model), with the aid of machine learning approaches, presenting two different projects experimental results validating the methodology and identifying further improvements with an image based 3D interactive viewer that automatically colour codes the deviations over the BIM model. However, is still challenging to link sets of unordered photos with as-planned models for monitoring construction progress. A lot of these images are uncalibrated, commonly with variable and uncontrolled lighting conditions and occlusions, factors that need to be considered for an accurate alignment and consequent successful measurements. In interior construction environment for example, data acquisition is very problematic due to the constant presence of multiple components such as equipment, temporary materials or movement of construction workers that can cause cluttered scenes [37] [38]. Therefore, innovative methods and techniques for data acquisition are required for a more advanced approach and standardized progress management methodology. These methods are explained in more detail in the section 2.2.

2.1.4 Software Applications

Throughout any type of facility or infrastructure lifecycle, BIM implementation and application relies on adequate software and tools. For each construction project phase different software can be found on the market providing different features within BIM environment. Based on the requirements of each project, the use of information by contractors, clients, etc., rests on the accurate use and choice of the software for each purpose. Among different capabilities such as their specific functions, it is essential to know the software interoperability with other software in search of an optimized and collaborative workflow that integrates different actors and tools.

Preparing the construction phase for progress management requires software with different capabilities. It is important that it enables merging of multiple models to create a federated model, and provides functionalities of quantity take-off, scheduling, 4D/5D simulations, cost management and progress monitoring. As mentioned, different software tools might offer different functionalities, so it is essential to know the accepted formats of each tool and its level of interoperability, so that communication and collaboration flow smoothly [4]. During the construction phase different software tools provide their users with visualization of models, documentation, and information management such as *Autodesk BIM 360*, *Dalux* or *Trimble Connect*. Some of the main available tools used for construction progress are *Navisworks*, *Vico Office* and *Bexel Manager*.

Navisworks Manage software by Autodesk, offers multiple uses being one of the most used in the market. It can import BIM models from diverse formats and create a proprietary federated model, and perform functionalities that range from quantity take-off and clash detection to scheduling and 4D simulation and animation, Navisworks is a powerful tool for construction coordination. and it is also capable of importing and view point cloud data either from laser scanners or photogrammetry.

Vico Office by Trimble is another comprehensive BIM tool for construction management. Model review, quantity take-off, cost estimation and project controls are some of its features which are supported by advanced functions of zone definitions, simulation algorithms for cost and schedule risk analysis, and planned vs actual schedule comparison with 4D views [4].

In focus on this study, *Bexel Manager* by Bexel Consulting is a IFC certified BIM software for construction project management based on advanced technologies and integrating 3D, 4D, 5D and 6D dimensions. All analysis are integrated in a single source of truth allowing the optimization of digital workflows within the same platform but also supporting collaboration with other software in an openBIM environment [39]. From cost estimation to Earned Value Analysis the software contains a powerful automated intelligent scheduling based on advanced algorithms that generate detailed schedules in seconds. Besides, its flexibility enables that schedules created in software such as *Microsoft Project*, *Oracle Primavera P6* or Bentley's *Synchro Pro* (scheduling-oriented software which also present capabilities for resource management), can be easily imported by *Bexel Manager* via XML format, requiring only the link between the activities and the model elements in *Bexel* afterwards. The capabilities of the software will be further explained in section 2.6.1 and explored in section 3.

2.2 Data Acquisition Methods and Technologies

In a recent report, Agarwal identified among others, that one of the main disruptive innovation applicable to construction, is the higher-definition surveying methods and techniques [40]. Construction project management using digital data acquisition technologies leverages accuracy and efficiency by decreasing human errors and the time-consuming methods. BIM alongside digital data acquisition, drones, and unmanned aerial vehicles for scanning, monitoring, and mapping is a very powerful tool. These technologies can be used individually or combined, to offer more comprehensive data [30].

The selection of data acquisition methods and types of technologies is essential and depends on the characteristics of the construction project. Omar and Nehdi divided data acquisition technologies in different groups, such as geo-spatial and imaging, and analysed advantages and disadvantages of each [41]. Geo-spatial technologies consist of barcoding, radio frequency identification (RFID), ultra-wide band (UWB) tags, geographic information systems (GIS), and global positioning systems (GPS). Imaging technologies are photogrammetry, laser scanning, videogrammetry and range images.

The RFID system consists of an automatic identification technology using radio frequencies to capture and transmit field data, and rely on two components, readers, and tags. These are working at a specific frequency, varying from low to extremely high frequencies [42]. Ghanem and AbdelRazig applied this technology to track materials and construction progress on steel pre-engineered building [43]. RFID and barcoding, have been successful technologies for material identification with applications in tracking resources, plant, and equipment deliveries, showing also great benefits in inventory management.

Similar to the previous technologies, UWB can be applied to short-range communications. Cheng et al. applied this technology in material location tracking successfully in construction projects, reenforcing the idea of its real-time location sensing and resource tracking efficiency in harsh environments [44]. In summary RFID, UWB or GPS are radio frequency technologies better suitable for tracking objects' locations. Compared to the others, a downside of using the GPS system in construction, is the limit of radio frequencies infrastructure in enclosed areas fully covered in indoor construction sites. RFID and UWB do not require a line-of-sight overcoming occlusions issues, and they also benefit from the low sensor complexity to target objects presenting an efficient deployment in construction sites [38].

However, not all construction elements can be tagged. Due to this pre-setting requirement, data collection based on the aforementioned technologies can only be applied to prefabricated objects. Additionally, it is infeasible to tag every element relevant for measurements, such as tiles. Benefits are restricted to the detection and identification of objects or equipment installed or brought to site [13], [45]. Thus, no sub-state is quantifiable at the object level to distinguish between the object's activity levels (e.g., wall paint or concrete cast in situ). Moreover, for progress monitoring, additional investment on equipment and human work would still be required [31]. In conclusion, the use of these technologies solely is not suitable for an advanced progress management. However, they can work as supporting approaches for other techniques.

The automation of progress analysis of construction activities has greatly benefited from the recent rapid growth of imaging technologies. The use of digital imaging to generate 3D as-built data and information about construction objects has been highly leveraged by the increasing refinement of data acquisition and high computing power performance essential for processing. Therefore, the implementation of vision-based technologies for construction processes automation is becoming more feasible.

The sub-process of data acquisition in the advanced progress management, is further developed below:

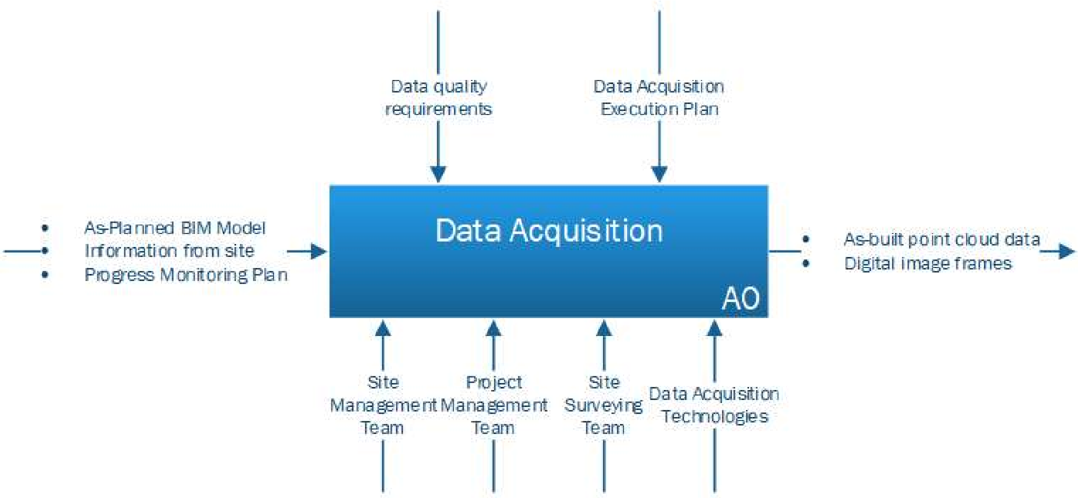


Figure 11 - IDEF0 for Data Acquisition

The outcome of the process is a point cloud[1] (laser scanning) or digital images frames (e.g., photogrammetry) depending on the type of technology used for data acquisition. This data is crucial for the comparison between as-built and as-planned, and its accuracy dictates the performance of the progress monitoring process. To achieve it, main steps are required before the actual capture of data on site. The process of data acquisition depends on selecting the technology and the sensor mounting method. There are numerous possible combinations. The data acquisition methods can be fixed devices, handheld devices, systems installed on unmanned ground vehicles (UGV) or unmanned aerial vehicles (UAV). Several research have been made to support the decision of which technologies and sensor mounting method should be used in each situation. Ekanayake et al. in [37], did an extensive research on construction progress monitoring on interior construction studying the best solutions for data acquisition technologies and methods indoors. When building indoors, multiple challenges related to limited visibilities, occlusions, camera movements, lighting, and the number of different objects, cause serious difficulties to the process of data acquisition to generate complete as-built data and models. Fixed cameras, for example, due to the limitations in range and also constant relocation due to work advancements can be challenging [31]. Han and Golparvar-Fard summarized the main issues of data capture lies on site conditions that hinder the ability to find good positions for time-lapse cameras that avoid occlusions, effective locations and alignments for photographic capture using smart devices, or identify areas that require scanning through UAV [35] It is clear that indoors and outdoors require different types of approaches, making the decision of which technologies and methods to use clinical, depending also on the type of project, stage, location, environmental conditions, etc. To provide helpful insight criteria and support for selection, Reja et al., proposes the dual concentric matrix in Figure 12 where technologies and methods displayed in their respective matrix rings and grouped according to colours and icons for a clear interpretation (low, medium, and high rating are shown using green, yellow, and red colour codes, respectively).

The required input for this process consists of the as-planned BIM model, information from site and progress monitoring plan. The progress monitoring plan is created before construction, with the goal of showing all the places on site to monitor, the exact timeline of data acquisition and required report based on scopes. It is also important to consider information gathered on site (e.g., environmental factors) that might hamper and influence the reality capture of construction progress. To monitor the progress is important to know which works are being performed along with their locations to support the creation of a path for exact data capture locations on site. This information, provided by the site management

[1] Point cloud is a set of data points in a tri-dimensional coordinate system, defined by the x, y, and z coordinates which represent object's surfaces. In some cases it can include the normal vectors of each point and RGB information [46].

team, crossed with the as-planned 4D BIM model and the progress monitoring plan, enables the creation/update of a plan for data capture (Data Acquisition Execution Plan) including all logistics [47]. When dealing with laser scanning for example, in order to minimize data acquisition time and ensure that the acquired scan data meets the requirements such as the defined level of detail, a scanning strategy plan should be defined in advance settling a scan planning [48]. Zhang et al., in [49], used a technique of "divide-and-conquer" to determine the laser scan plan in a faster manner, by cluster identified target points that needed to be scanned to finally set scanning positions for each group. Prior to each data capture on site, the plan must be reviewed. Possible new update might be required according to latest information.

Another important control on this process is the data quality requirements definition. The level of detail (LOD) and accuracy are important aspects since different objects require different levels of definition. The former measures the data density while the latter indicates the tolerance of positioning and dimensional errors [49]. For progress management, it is important to understand which objects require more or less information. As an example, a flat concrete wall consists of a simple geometry, so it will not require a great level of detail (data density) for its identification. Instead, the LOD may need to be increased for more complex shapes such as openings. The U.S. General Services Administration (GSA) published guidelines related to 3D imaging services and assessment principles to ensure the achievement of specified requirements [50]. Methods for automated scan planning on construction sites have been developed adopting these guidelines. They defined four levels of detail for point cloud (LOD 1, 2, 3 and 4) corresponding to four different areas of interest – Being LOD 1, total project area; LOD 2, building; LOD 3, floor level; LOD 4, room or artifact. Each level corresponds to a criteria on the acceptable dimensional variations and dimensions of the smallest recognizable feature [50]. On another study, Rebolj et al., defines elements according to their size (large, medium, small, very small), with the purpose of relate them to construction phases (slabs, columns, masonry works, services and finishing works) and the point cloud quality criteria accordingly [51]. Lastly, different areas and tasks on a construction site may require different levels of detail. Specifying the LOD requirements for each data collection, enables the collection of imageries with all information required while avoiding unnecessary heavy data, contributing to less wasted time and resources in data capturing and processing.

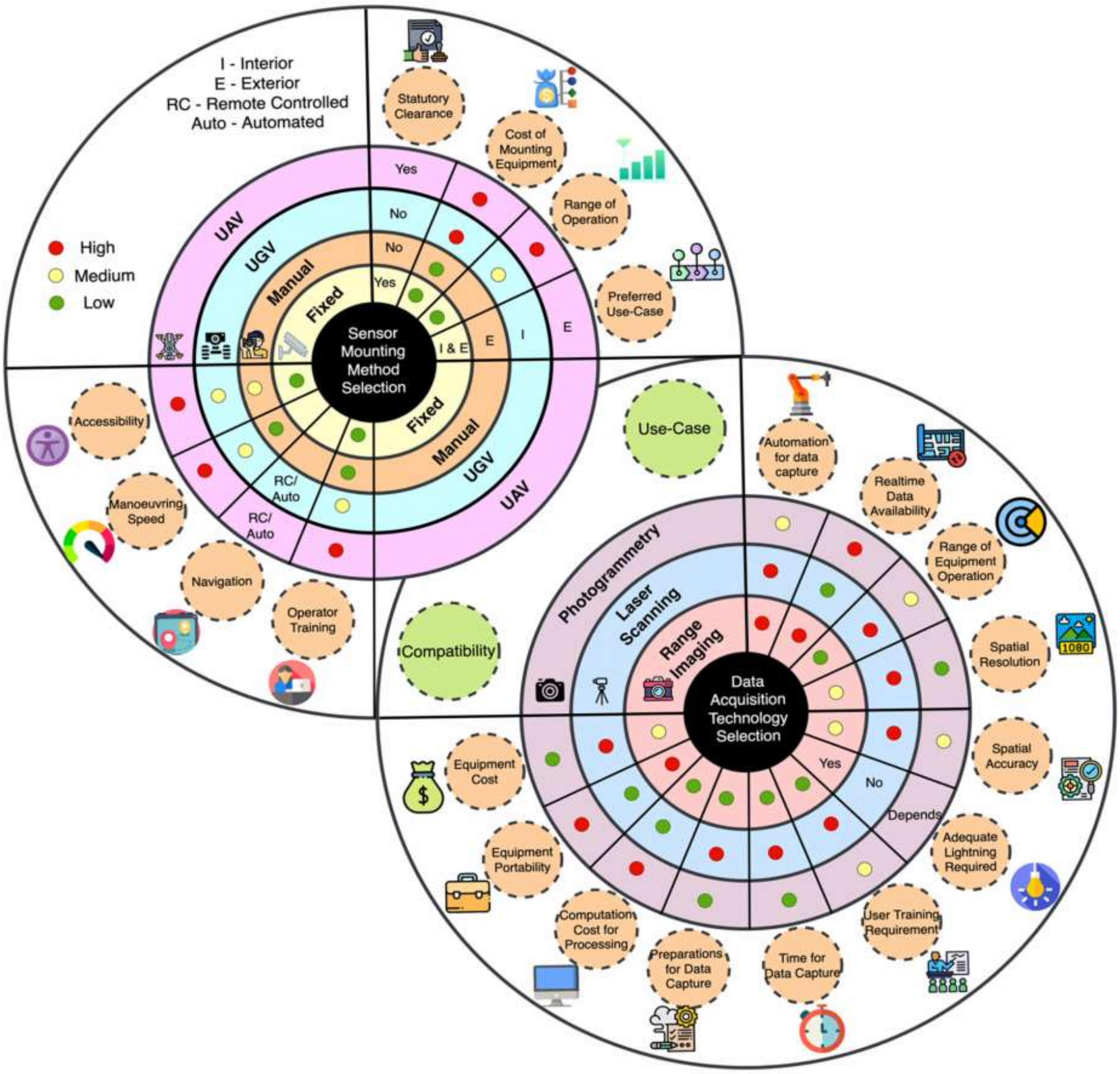


Figure 12 - Dual matrix for data acquisition method and technology selection [34]

2.2.1 Photogrammetry

Photogrammetry is one of the most used techniques to retrieve geometric information of the as-built construction scene. Through the process of collecting, measuring (e.g., position, size, and shape of objects), and interpreting digital images captured on site, including the generation of a as-built 3D point cloud, this technology enables the collection of reliable information regarding physical objects and settings. To enable the creation of an accurate 3D as-built point cloud of all construction elements on site, the process requires taking a set of overlapping photos of the objects on site, from different positions and angles, allowing pairing and matching of common points in neighbour frames [42]. This registration of photo frames together, requires some motionless site control points in each photo frame for an accurate 3D as-built scene generation. The conversion of the digital frames into the point cloud is normally performed through photogrammetric software such as *VisualSFM*, *Agisoft Photoscan*, *Patch-based Multi-view Stereo Software* (PMVS) and *Clustering Views for Multi-view Stereo* (CMVS) [52], which are based on SfM[2] (Structure From Motion) and MVS (Multi-view stereo) algorithms [54].

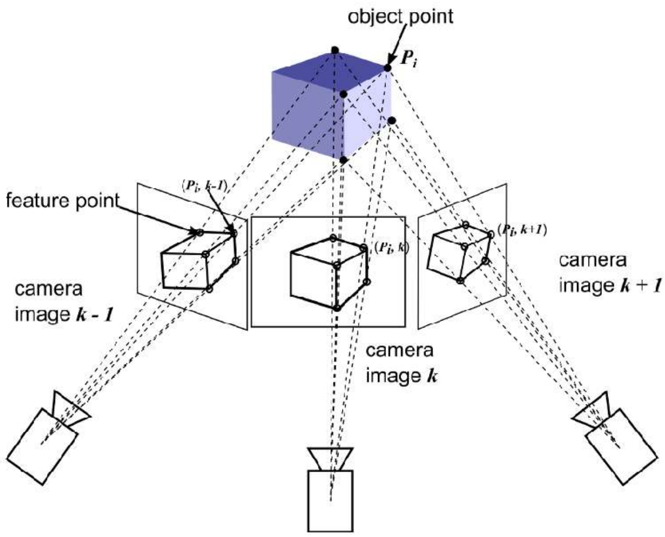


Figure 13 – Multi-view geometry principles (SfM and MVS). The capture from different locations allows the assignment of different object's points to positions in 3D space allowing future 3D modelling [55]

Photogrammetry is the most cost-effective technology for an effective 3D point cloud. Another advantage is that the image frames can be later utilized to extract information useful for the object texture and colour. However this technique's results is reliable on lighting conditions on site [54].

Omar et al., in [52], used photogrammetry to develop a system for monitoring, updating and controlling construction site activities in real-time in order to identify deviations of as-planned schedules detecting delays and notifying project managers and clients. It was used and tested on concrete structure works phase demonstrating great accuracy on outdoor construction activities. To construct the 3D point cloud from the images gathered (Figure 14), the author used *Agisoft PhotoScan* software.

[2] SfM is a technique based on the combination of algorithms for photogrammetric 3D reconstruction. It makes use of ordered or unordered photographic records to recreate camera motions and structures of a scenario. With no previous geometric or semantic information, this process interrelates all the images with each other, find the correspondences through advanced feature descriptors, and then eliminates misaligned images to get relative camera positions and the point cloud structure [53].

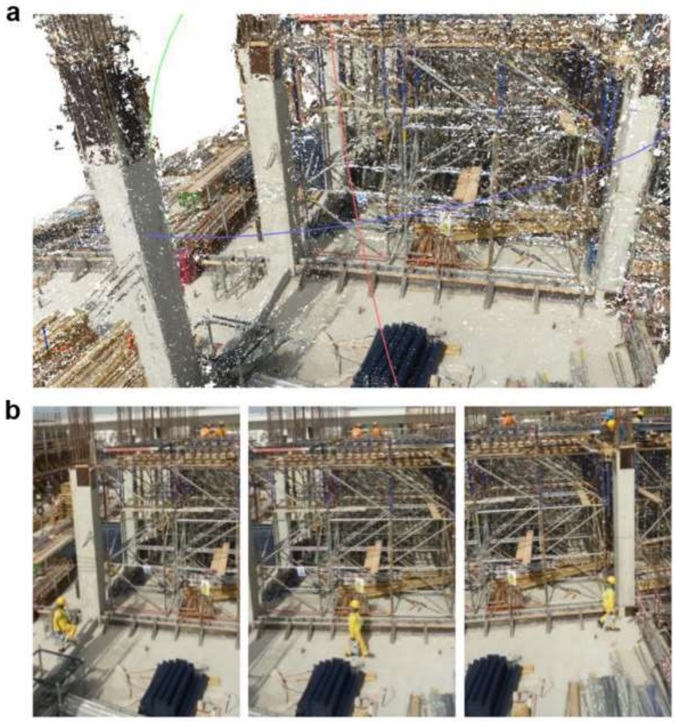


Figure 14 - a) Point cloud from photos taken on site. b) Photo samples for point cloud. [52]

2.2.2 Videogrammetry

The videogrammetry technique is similar to photogrammetry, with the difference that images are extracted from recorded video from the construction site. Videogrammetry is a process of 3D point cloud reconstruction through the measurement of coordinates of object points from two or more video frames. Video frames are sequential, thus the pixels in each frame are progressively rebuilt using the information from the frame before [56]. This feature of videogrammetry makes it easier to recreate civil infrastructure scenes in faster way. With the use of high resolution cameras, videogrammetry has improved the progressive scenes reconstruction level of accuracy [41]. It has also been used for indoor and outdoor progress tracking of construction activities by integrating computer vision and machine learning algorithms [51], [53], [57].

The generation of point clouds via moving cameras is enhanced by advancements in Simultaneous Localization and Mapping (SLAM) techniques. It consists of a framework that dynamically estimates camera positioning of the acquired image sequences (or video) recreating map of the environment for 3D reconstruction automatically in real time, with no prior knowledge, keeping track of positions with respect to the surrounding environment. This incremental map consists of feature correspondences from the video frames, enabling the generation of an accurate point cloud of the setting [53]. The fast advancements in autonomous technologies such as UGV and UAV for on-site data collection (Figure

15), will lead to a more significant application of the SLAM technique reconstruction in the industry [34].

Figure 15 - Combination of UAV with 3D imaging technologies for data acquisition on construction site [58] .

2.2.3 Range Images

Range images are also known as depth images. Each of these images' pixels acquired with depth cameras, contain values with the distance between the sensor and any object's surface in a scene which enables the further shaping of any element. RGB-D cameras (red, green, blue and depth) have great capacity for spatial sensing, capturing both colours and depth images in almost real time, which can be used to detect characteristics of the construction objects [41]. By transforming each range image to a set of 3D coordinates for each pixel, this technology is able to produce a point cloud representing an environment through multiple views without additional processing for point cloud registration. The accuracy of this technology relies on short range applications, with the advantage of being unhindered by the backlight, covering wider fields of view [56].

Son and Kim, in [59], developed a method based in range imaging, proposing an automated 3D structural component recognition and modelling method, employing colour and 3D data acquired for use in construction progress monitoring. By testing it on site, the method proved its suitability and application for progress assessment, which was demonstrated using an actual on-going construction project on the structural framing assembly phase.

2.2.4 Laser Scanning

Laser scanning, also known as LADAR (Laser Detection and Ranging), recently became a common technology to obtain 3D point clouds. It works by releasing a laser pulse directed to a target and based on timing the round-trip time it calculates the distance to the target. Hence, the capture of millions of 3D points can be done in a very short time, by one laser scan [60]. The output raw data is a point cloud, which can be visualized and reviewed through specific software at high resolution and used for accurate wide range measurements. The capability of quickly collect data from site and provide great amount of information regarding the construction elements surface in the form dense set of 3D points with relatively high quality, by simply using a tripod, a laser scanners and a computer makes this technology highly valuable [61].

Despite the accuracy and efficiency in collecting volumetric data, some situations can become challenging for the use of this technology. The interior construction settings can be difficult for data collection with laser scanners, due to reflective materials such as metal studs and pipes and transparent indoor elements that do not reflect laser pulses, like glazed doors and windows. Furthermore, the congested internal construction works and the need of a clear line of sight can create challenges for the application of this technology [37].

Its increasing application in the data acquisition field for progress monitoring is due to its accuracy. However, being an expensive technology that requires experienced surveyors for its efficiency and calibration, along with the previously mentioned challenges, impedes laser scanning to be more widely employed on construction sites [51].

Maalek et al., in [62], developed a robust framework to determine the progress of concrete work, using terrestrial laser scanning point clouds for data acquisition, and applied it successfully on a construction project revealing high accuracy. The extraction of structural components from the point cloud, enables the comparison of as-built works with as-planned building information model to automatically identify schedules and dimensional discrepancies. On similar studies [60], [63], Turkan et al. and Kim et al., developed an automated system for 4D object oriented progress tracking to update the construction schedule using 3D point clouds acquired through laser . To obtain insight regarding the progress on site, the 3D point clouds acquired are firstly registered[3] with the 4D as-planned model in the same coordinate system (Scan-vs-BIM approach explained on section 2.3.1). Subsequently, through the recognition of as-built objects the progress assessment and schedule updating are performed automatically.

[3] Point cloud registration is defined as the process of alignment between two or more 3D point clouds representing the same scenario, into a common coordinate system.

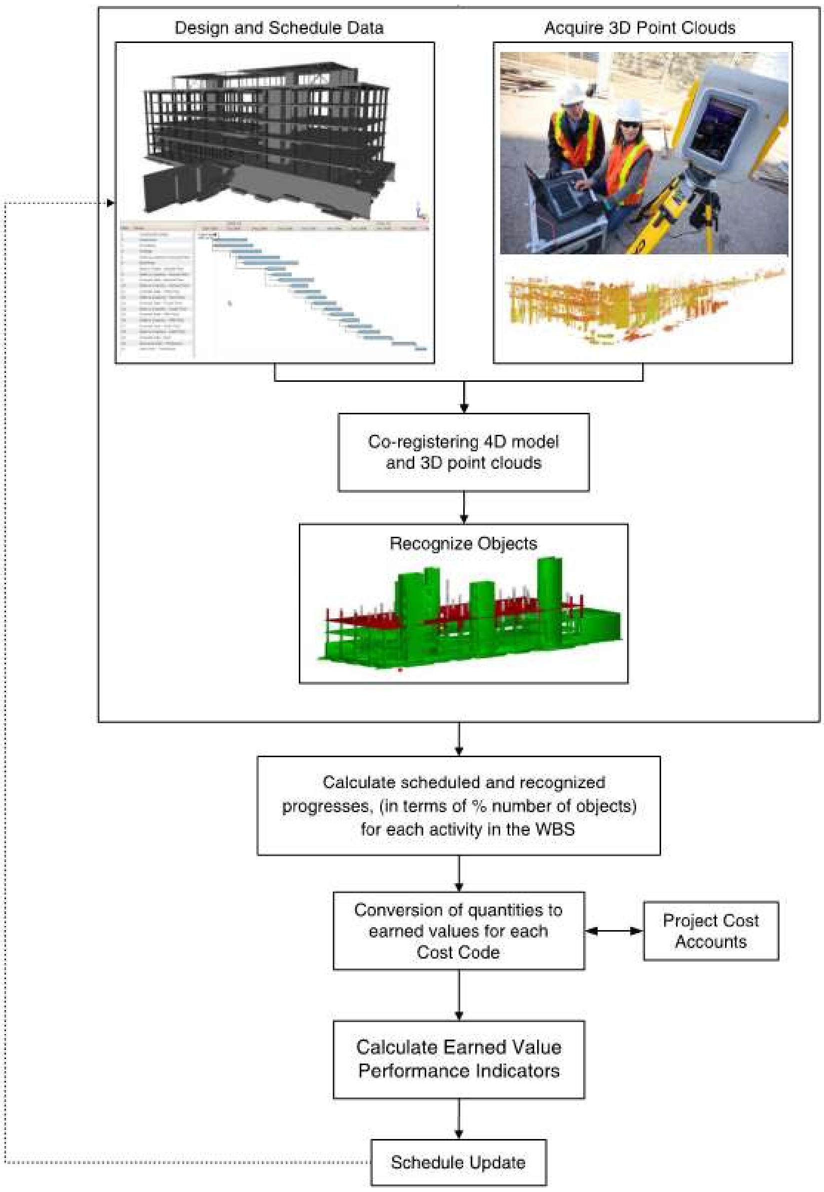


Figure 16 - Conceptual view of the system by Turkan et al., for progress estimation and schedule update [60].

The selection of one particular technology may differ according to the type of information required, the setting where the data will be acquired, and the accuracy level needed. Hence, to wrap up and to compare the different imaging data acquisition technologies (in terms of cost, capturing speed, processing time, etc.), the Table 1 presents the benefits and limitations of each of the aforementioned techniques.

Table 1 - Comparison of 3D imaging methods for as-built data acquisition (based on [41], [42], [56]).

Techniques	Benefits	Limitations
Photogrammetry	• Straightforward configuration • Accuracy • Cost-effective field data collection • Portability • Provides information about the material, texture, and colour of the target object	• Manual 3D data retrieval • Non-real-time data retrieval • Sensitive to the surrounding light condition • Low spatial resolution • Limited range distance (tens of meters) • Computational complexity of photogrammetric surveying • Less accurate than laser scanners in generating point clouds
Videogrammetry	• Straightforward configuration • Accuracy • Cost-effective field data collection • Portability • Provides information about the material, texture, and colour of the target object • High spatial resolution • Real-time data retrieval	• Limited automated 3D data retrieval • Sensitive to the surrounding light condition • Limited range distance (tens of meters) • Computational complexity of photogrammetric surveying • Less accurate than laser scanners in generating point clouds
Range Images	• Automated 3D data retrieval • Less sensitive to lighting condition-operation day and night • Affordable equipment cost • Portability • Provides information about the material, texture, colour, and depth of the target object • Real-time data retrieval • Less costly than laser scanners	• Short-range distance (meters) • Low spatial resolution • Less accurate than photogrammetry and videogrammetry • More costly than photogrammetry and videogrammetry
Laser scanning	• Automated 3D data retrieval • Ability to scan actively in darkness and shaded areas • High accuracy in generating point clouds • Not sensitive to lighting condition-operation day and night • Long-range measurement (hundreds of meters) • Ability to scan a large area • Simple and well-defined internal coordinate system	• High equipment cost • Nonportable • Non-real-time data retrieval • Not as accurate as photogrammetry and videogrammetry • Occlusion problem and the need for a clear line-of-sight • High storage capacity is needed

Finally, to overcome the constraints associated to the standalone use of these techniques, the combination of different technologies can improve the performance of data acquisition. In a attempt to improve data collection from construction sites in terms of speed and accuracy, El-Omari and Moselhi, in [64], developed a method based on the integration of photogrammetry and 3D laser scanning for data acquisition to provide support for the processes of progress tracking and project control. To validate the method, they tested its application on a building under construction and presented promising results in terms of time and cost efficiency, supporting the integration of different technologies for diverse types of projects. Moselhi et al., presented in [42] an extensive analysis of several integrated data acquisition systems, describing benefits and limitations of each combination of technologies, showing all their potentialities.

2.3 Information Requirements

2.3.1 Scan-to-BIM and Scan-vs-BIM

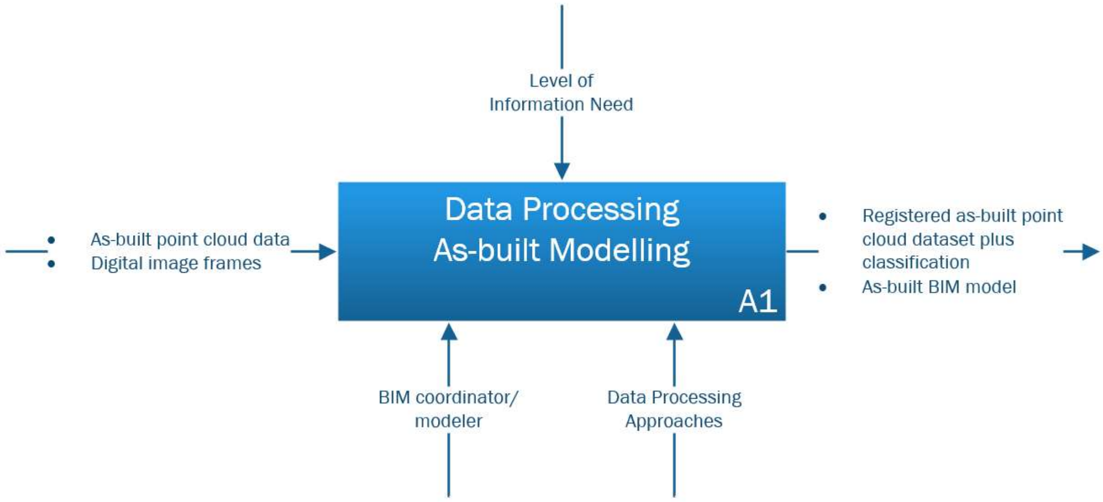


Figure 17 - IDEF0 for Data Processing.

With a pre-established as-planned building information model, and point clouds generated through spatial and geographical information collection of the environment, different approaches can be used to compare as-built information with as-planned for the progress assessment of the construction project:

- Scan-to-BIM
- Scan-vs-BIM

In both techniques, after collecting point cloud data from site, an important first step is the data pre-processing, in which the sets of point clouds from the acquired scans are filtered, merged and aligned into a shared coordinate system establishing a single point cloud, in a process known as registration[4] [65].

➢ Scan-to-BIM

With the use of intelligent proximity algorithms and human intervention is possible to convert the point cloud generated into a model. The outcome is an as-built 3D surface containing spatial data of all the elements present in the data capture, where machine learning algorithms (such as RANSAC[5] or Hough transform[6]) are applied to detect simple planes or more complex features [61], [65]. The Scan-to-BIM is a concept and approach that concerns the process of scanning a construction project and from the

[4] Registration is the alignment of different sets of point clouds with one another.
[5] RANSAC or Random Sample Consensus is a robust plane detection algorithm.
[6] Hough Transform is a well-known algorithm for detection of parametrized objects.

generated point cloud captured data, create an as-built BIM model representing the construction scene current state [42].

The Scan-to-BIM approach is less frequently found in research due to being a time-consuming approach (from gathering data to generating the BIM model) that can be error-prone, while also requiring costly equipment [54]. A good level of automation was achieved by this method including the generation of a 3D surface model and semantic information. However, the as-built BIM model still requires an extra step of transforming the surfaces into actual BIM solid elements. Even though advanced algorithms have been developed to help the automation of the modelling step, this has not been fully accomplished yet to fit the construction domain (partially due to complex geometries, occlusions and cuttler). Thus, since different levels of manual intervention is required, this sub-process of Scan-to-BIM is still semi-automated [66].

A framework for Scan-to-BIM application oriented process is proposed by Wang et al., in [67], identifying four key steps of the process including, identification of information requirements, scan data quality requirements, scan data acquisition and as-built BIM model reconstruction (Figure 18).

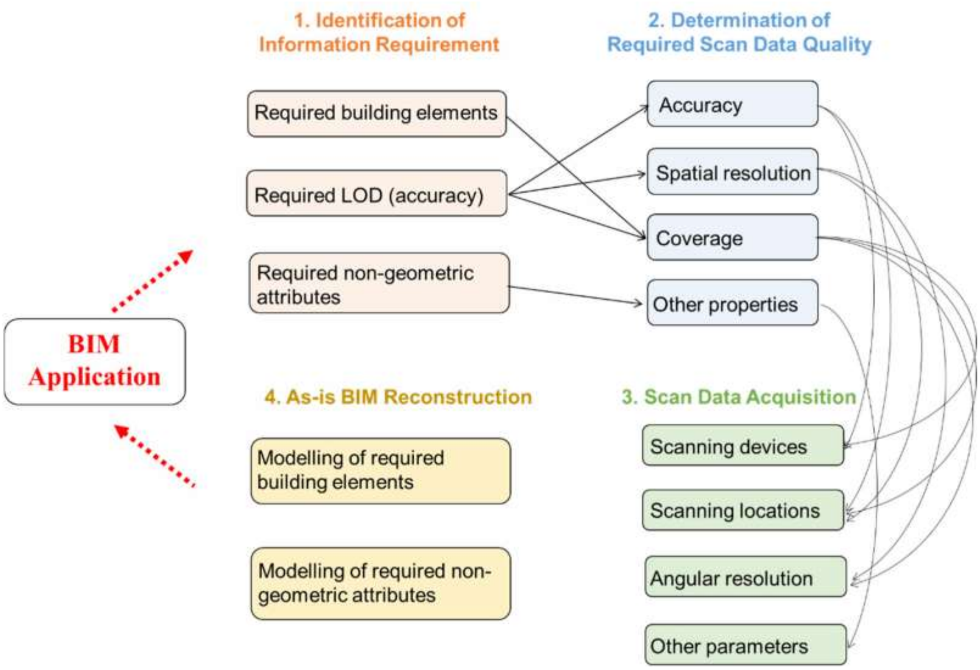


Figure 18 - Scan-to-BIM framework proposed by Wang et al. [57]

Similarly, as previously mentioned on 2.2 the framework proposed identifies the necessity of defining the required information for an accurate as-built model for the intended application, enabling the required point cloud data quality determination to avoid waste of time or over data collection.

For the process clarity, the list of required building elements should be identified employing a classification system (such as UniClass or UniFormat) useful for progress management, which can be based in elements, or activities for example. Furthermore, the concepts of LOD and non-geometric attributes can be replaced by the concept of Level of Information Need (LOIN) introduced by the ISO 19650-1 [68]. Within this concept various metrics can be used to determine the information to be delivered such as geometry, alphanumeric data (e.g., surface properties of building elements), and documents for example for the intended as-built model elements.

The as-built automatic modelling of the construction scene elements captured on site, consists of geometric modelling and object recognition[7]. The former aims to model the geometry of the required building elements, by detecting planes or modelling parametric surfaces, while the latter targets the labelling the scan data into object categories (e.g., floor, columns). There are different strategies and approaches to support the automated creation of as-built model building elements [34], [67]:

- Heuristics/Hard coded knowledge-based approach – it uses pre-coded domain knowledge to identify elements from as-built point clouds. Geometrical type of heuristics would first detect[8] planes from the point cloud followed by the labelling of each detected plan based on hard coded prior knowledge (e.g., walls are vertical and perpendicular to floors which are horizontal, etc). Size, position, orientation, topology[9] are the most used categories. Heuristics can be divided in geometry, rule-based, relationship-based.
- Supervised learning-based approach – through large sets of already labelled scan data into object categories, machine learning algorithms can be trained to classify new point cloud data. Support vector machines (SVM) and random forest (RF) are algorithms that will then use geometric and semantics features such as shape descriptors, and RGB or HIS (hue, saturation, intensity) colours for classification. Following the classification of each point cloud data point into distinct item categories, this approach is used to model individual points as building elements from different categories by applying geometric modelling techniques.

Besides geometry itself, required modelling of non-geometric properties is also considered - spatial relationships between elements, modelling of materials and surface properties. The elements surface properties comprising colour and reflectivity values can be related to each point of the laser scanned point cloud data. However, it is not possible to derive materials and spatial relationships directly from the point cloud, requiring additional data processing [67].

[7] Object recognition means discerning the type of object through the analysis of the data features. However, Scan-to-BIM and Scan-vs-BIM vary on this matter. In Scan-to-BIM, it means to recognize the object type, which can have multiple instances (e.g., several pipes with identical features are recognized as different instances of the same object type). In Scan-vs-BIM it further enables the identification because each recognised object refers to a unique object (of the specific object GUID) from the as-planned BIM model. These algorithms can recognize object instances or object categories.
[8] Detection refers to the process in which the presence of an object is identified in an acquired point cloud [69].
[9] Topology refers to elements topological relationships – floor intersected by a wall.

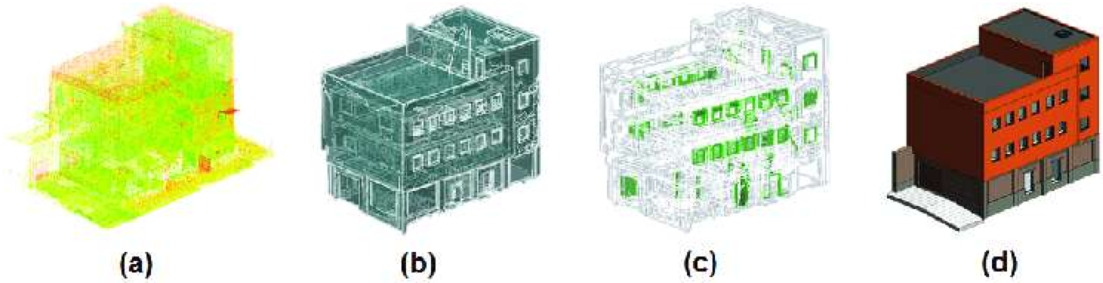


Figure 19 - Scan-to-BIM workflow from [70] : (a) point cloud, (b) vector model, (c) labelled data, (d) as-built BIM model

Xiong et al., in [71], established a method to automatically reconstruct a structural semantically rich information model from a point cloud by using an algorithm capable of extracting geometrical surfaces and recovering semantic information by the use of their shape-grammar or contextual relationships, despite occlusions and clutter present in the scene.

On another study from Perez-Perez et al., [72], a new deep learning method was introduced for semantic segmentation of different specialties and classifying elements as floors, columns, beams, walls and pipes. From an unordered point cloud scene, the process utilizes CNN[10] (convolutional neural network) and RNN (recurrent neural network) algorithms to assign semantic and geometric labels to classify the points, showing promising results for the optimization of Scan-to-BIM automation of buildings.

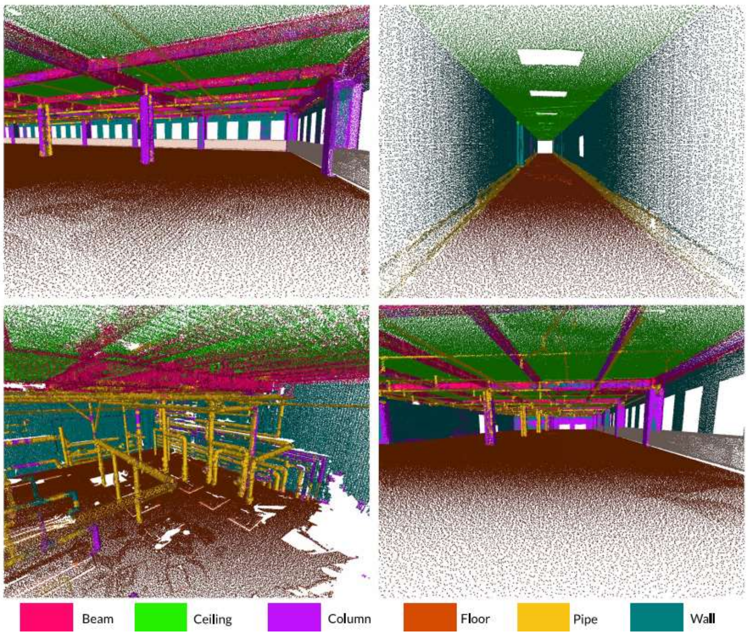


Figure 20 - Results from classification methodology introduced by [72]

[10] CNN and RNN are Deep Learning algorithms. Based on artificial neural networks and representation learning, deep learning is a subset of machine learning approaches that can be supervised, semi-supervised or unsupervised.

Anagnostopoulos et al., in [73], developed a semi-automated approach to retrieve object boundaries from the as-built point cloud and estimate their adjacency, to create the IFC as-built model. After extracting the detected objects boundaries, spaces and object entities are defined by further mining volumetric and parametric information such as volume within enclosed spaces, and height and thickness of walls. Object extracted are categorized and their relationships identified, enabling their conversion into IFC entities (e.g., floors - ifcSlab), through an ifcCompiler.

On a different research [74], Macher et al., states that the aforementioned study is one closest to BIM, given that wall objects are defined by volumes. Additionally, they further developed a methodology for 3D semi-automatic reconstruction of indoor building environments from point clouds, for their integration in BIM software. After the point cloud segmentation into planes and point classification into categories, the automated modelling of the structural elements (walls and slabs) was performed by first describing their geometry into an open data-format which then, by using FreeCAD software tool and a python script was translated into an IFC BIM model.

- Scan-vs-BIM

Besides Scan-to-BIM applications, the technology advancements of 3D modelling and BIM brings innovative approaches, such as the Scan-vs-BIM (in analogy to Scan-to-BIM). This approach represents an object-based detection technique, which by aligning laser scan point clouds acquired during construction with as-planned BIM models, enables the comparison of the two based on proximity metrics. BIM objects can then be automatically recognized and more importantly, uniquely identified[11] [51], [75].

Furthermore, there is a growing trend in computer vision to improve algorithms through the vast previous knowledge of construction progress provided by BIM, varying from elements' properties such as geometry and material, to information on as-planned schedule. Besides the use of as-planned BIM model for Scan-vs-BIM approach that supports the alignment of 3D spatial data to identify discrepancies in the construction progress [36], BIM can help filter outliers and refine the generated point cloud [59], assisting also with the object detection in cluttered[12] 3D data [32], [69].

Kim et al., in [63], applied machine learning algorithms to match the as-built data to BIM (Scan-vs-BIM) and classify elements. The method to determine the progress status of each element, works by extracting the features of the as-built data and matching it to the elements in the as-planned BIM model,

[11] Identification refers to when a specific object can be discerned. More specifically each recognized object from the point cloud can be matched to a specific object in a known as-planned object list (e.g., recognized pipe is discerned as being a certain pipe present in the project as-planned BIM model).
[12] Cluttered data denotes a disorganized collection of point cloud data in information visualization.

where each element's matching 3D data was then classified as a column, beam, slab, etc., to finally assess the project's progress.

Maleek et al., developed a framework for the semantic labelling and the extraction of structural elements acquired at regular concrete construction projects, enabling the automatic as-built vs as-planned comparison for progress monitoring [62]. With the use of machine learning methods, the registered point cloud is first submitted to a process of robust planar and linear segmentation followed by semantic object recognition using relationship-based heuristics. Finally for comparison between as-planned BIM model and as-built data, the corresponding objects are identified using a threshold (50mm) (Figure 21). This means that an object from the as-built point cloud will correspond to a specific object from the as-planned model if its geometry is located within this limit.

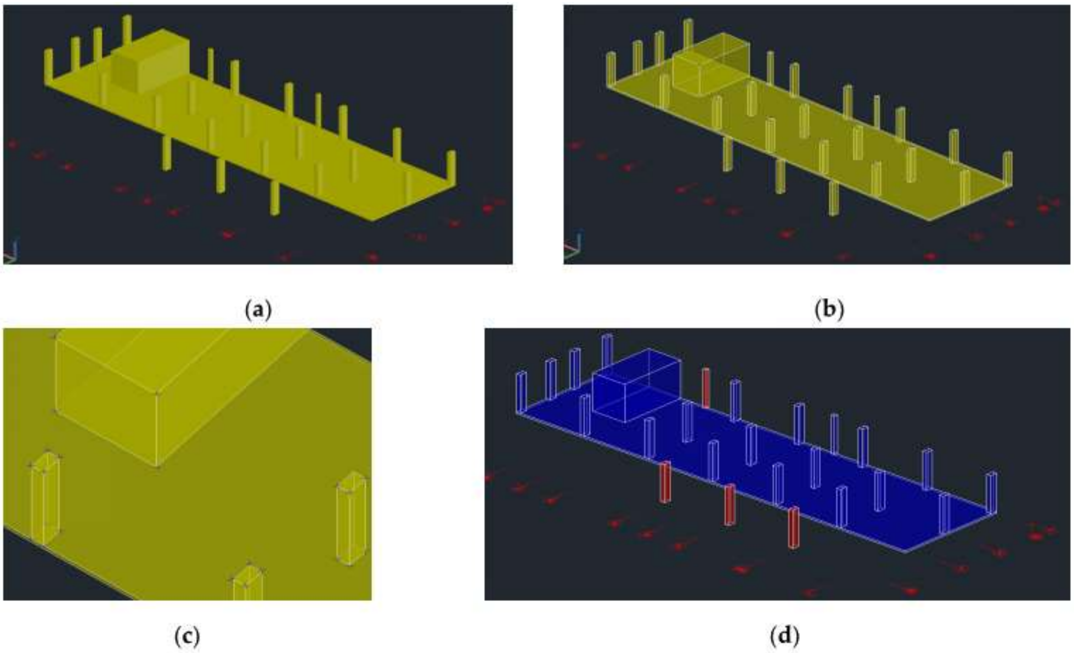


Figure 21 – (a) As-planned model; (b) as-built identified columns superimposed on as-planned model; (c) zoomed view of the superimposition of as-built identified columns edges (8 vertices in blue); (d) schedule comparison where blue – on-schedule activities (identified objects) – and red – behind schedule activities (objects not found) [62].

On another study, Turkan et al., in [76] presents an automated construction progress tracking and schedule updating system that combines 3D object recognition algorithms with 4D schedule data, where after the object recognition and identification is completed, progress assessments are done for each activity impacting the automatic update of the schedule.

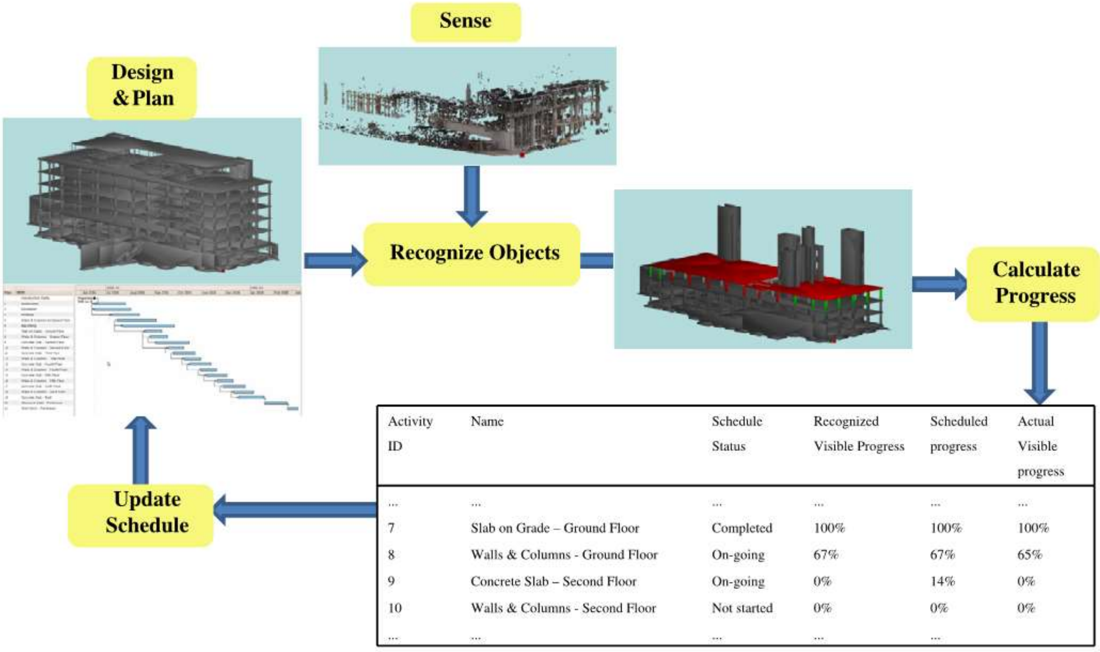


Figure 22 - Workflow from Turkan et al., for automated progress measurement and schedule update [76]

In [75], Bosché et al., a Scan-vs-BIM approach was proposed, to track the as-built MEP (mechanical, electrical, plumbing) works on site, that uses the as-planned BIM model to assign points to a BIM element in close proximity. It starts by decomposing the as-planned model into points (as-planned point cloud) with the same spatial resolution of the as-built point cloud. Both point clouds are then registered through an iterative closest point[13] (ICP) method, and corresponding points are matched by respecting previously determined spatial similarity criteria. The as-built data is finally labelled as the element corresponding to the as-planned point cloud.

Scan vs. BIM is a powerful approach for as-built progress monitoring enabling an easy implementation and identification of key elements directly from the as-planned BIM model. However, it presents some downsides. An example is the unreliability of the approach if the distance between as-built and as-planned is larger than the discrepancies criteria previously defined. There might be issues of false negatives, where the limitation of deviation between the actual and planned position of elements is too restrictive, leading to objects that are actually present are not recognized [62].

Scan-vs-BIM works well for structural works tracking, but its performance drops significantly in the case of MEP works since the geometrical discrepancies might be bigger due to the nature of this trade. For example, any as-built object placed further away than 50mm (e.g., predefined threshold) from the as-planned model, cannot recognized. [77].

[13] The iterative closest point (ICP) algorithm is widely used in point cloud registration. Classic method of rigid registration.

To overcome limitations of both Scan-to-BIM and Scan-vs-BIM techniques, a research by Bosché et al. [77], proposes the use of the two approaches for a more robust automated construction monitoring of MEP works, providing an automated progress management including also support for the delivery of as-built models. It proposes an object recognition method that not only is used to infer recognition from identification (as-built data vs as-planned data) but also to estimate to which extent the objects are built as planned. The combination of these factors enables the estimation of the percentage of elements built as planned.

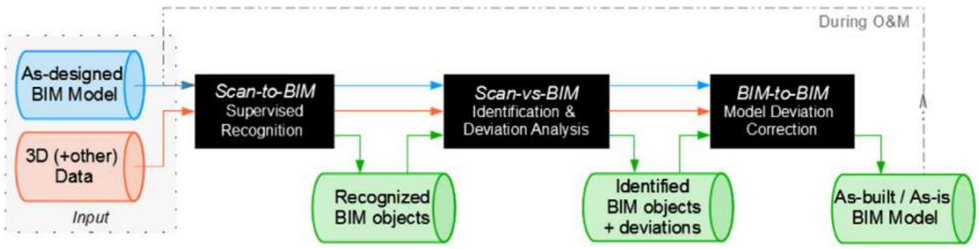


Figure 23 – Data process workflow for life-cycle BIM model as-built information management by Bosché et al. [77].

2.4 Dynamic Scheduling

The implementation of every construction process is based on planning and scheduling. It is known that almost every construction project drifts away from what was planned in the first stage and dynamic changes are frequently required in diverse management plans. The great level of uncertainty present within construction projects come from different factors which ultimately cause time and cost overruns. One of the methods to accommodate this issue and control time and cost overruns is the dynamic scheduling. Dynamic scheduling is a method of updating the schedule at the instance of time [78]. According to [27], dynamic project scheduling consists of three components, project scheduling (baseline schedule), risk analysis (of the project schedule) and project control (project's progress). A solid baseline schedule together with the knowledge of the sensitivity of each construction project activity on the project's time and cost components, constitute the inputs during the project control process to provide proper support for decisions and corrective actions if the project performance is at risk (the topic of project progress control will be further in explained in the next section).

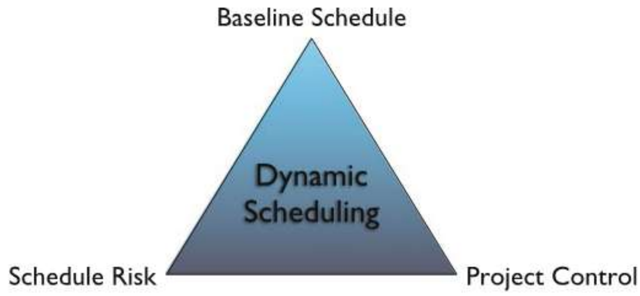


Figure 24 - Three components of dynamic project scheduling[27]

When developing the project baseline schedule prior to the execution works on site, a list of activities of the project's construction is set with the project's objectives and goals in mind (WBS). Along with it, precedence relations and resources availabilities and requirements enable a final activity network that ultimately leads to the making of the construction baseline schedule defining, start and finishing times for each of the activities. During the execution phase and project progress control, the project is monitored to evaluate its performance in relation to the existing schedule, infer deviations and take corrective actions, including updating the schedule. The mechanism is shown **Error! Reference source not found.**.

Figure 25 - Dynamic Scheduling mechanism.

The schedule update can be done in several ways, reactive, proactive, and predictive-reactive [27], [79].

- Reactive scheduling does not try to cope with uncertainty or risk factors in creating the baseline schedule. Revisions are done during execution while monitoring progress, and when unexpected events occur, and deviations are significant, real-time decision and adaptions to the schedule are made on a expedite way on the resource level (this reschedule process is more seen in small construction companies). Priority rules are often used and consist in select the job with highest priority to be processed in case of conflict between activities.

- Proactive scheduling takes uncertainty into account to establish a buffered[14] schedule, making it robust against possible uncertain events. This approach relies on ongoing cycles of progress updates usually to activity duration and resource levels, but rarely to logic[15] (schedule updating). This robust schedule accommodates possible uncertain events, decreasing the number of reschedule within certain ranges. Similar to many construction projects planning, the conditions of this technique are based baseline production, followed by periodically update (Figure 26) of actual progress numbers and remaining durations, without adjustments to the original schedule logic (common in traditional and regular construction projects, where the work sequence is clearly deterministic, and the disruption probability is relatively low).
- Predictive-reactive scheduling is based on the generation of a baseline schedule with the same principles as of the proactive schedule, which is then rescheduled (logically revised) based on real-time events. This is similar to production of revised schedules in construction for major real-time disruptions and it is the most commonly used approach.

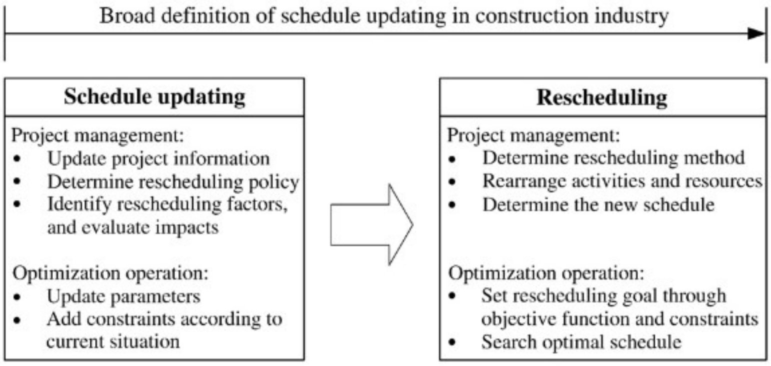


Figure 26 - Schedule updating and rescheduling – comparison [80]

Real-time events that can cause disruptions to schedules are categorized in project-related events (e.g., additions or omissions to original scope, or changes of sequence and priorities), resources-related (e.g., shortage of material, insufficient capacities of assigned resources), and operations related (e.g., quality of output, changes in deliverables' specifications, wrong estimate of resources' productivities). The rescheduling process in the presence of real-time events require addressing of two issues. How to react and when to react. Thus, real-time events can trigger reschedule which can be further categorized in two different types of strategies (how) and three different types of time frequency, rescheduling policies (when) [79], [81].

[14] Schedule Buffer is a block of time added to a project individual activity or an entire project schedule that protects scheduled tasks and project due dates from the impact of uncertainty and variation to the deliverable placed on a schedule (delays and overlays).
[15] Logic is the basic premise behind scheduling. It defines the relationships between activities (e.g., certain activities cannot occur before others are complete).

- Strategies
  - Schedule repair: mitigating real-time event by minimum adjustments to the portion of the schedule related to the event (less computational effort).
  - Complete rescheduling: regenerating project from scratch. The great computational effort and time makes this approach less preferable despite helping to maintain near optimal solution. Moreover, it can result in instability and lack of continuity, leading to additional production costs and increased system nervousness[16].
- Policies
  - Period rescheduling policy: process of rescheduling every predefined time period regardless the number of real-time events occurred within this period.
  - Event-driven rescheduling policy: process is triggered with any disruptive real-time event occurrence.
  - Hybrid rescheduling policy: rescheduling happens periodically regardless of the events happening throughout, but some of the events are predefined as triggers for a new rescheduling intermediate process.

Generally, in construction industry the scheduling and rescheduling processes are mostly carried out on periodical basis, where all the events that occurred throughout are grouped. As a result, the Periodic Rescheduling Policy represents the most appropriate policy for construction projects as it addresses the key requirements of the real-time construction environment (rescheduling when significant predefined events occur and periodic small-scale rescheduling that is typically required to optimize the resources usage based on the current progress).

Rescheduling techniques represent the method or algorithm to repair or reschedule the project plan through the means of computation, such as heuristics, knowledge-based systems, neural networks, hybrid techniques, etc. Research into optimising project scheduling has primarily been aimed at either optimising resource use or time cost trade-offs.. It is generally accepted that the presence of resources under limited availability is a matter of degree within construction. The basic project scheduling techniques (lower complexity), such as PERT[17] or CPM[18], assume the projects' development with an infinite resource capacity. This simplicity leads to a restriction on their use, limited to simple and straightforward projects where resources are assumed as relatively unconstrained and so they remain ignored for scheduling. However, their principles are still applicable to more advanced techniques.

The resource-constrained project scheduling techniques (RCP) have their main focus on developing algorithms and procedures to solve complex problems taking the limited availability of resources into

[16] System nervousness is an effect where the future order forecasts, given to suppliers for example, so that they can organize their affairs and plan production, displays severe variability.
[17] Program evaluation and review technique
[18] Critical path method

account. The vast majority of resource-constrained scheduling techniques are based on exact and heuristic procedures. The former aims at finding the best possible solution for the scheduling problem (frequently limited to small projects with specific assumptions). The latter targets on finding a good solution which might not be optimal (more realistic projects with different assumptions and bigger dimensions) in a reasonable computational time. Even if these procedures do not ensure an optimal solution, due to their simplicity and generality to a wide variety of construction projects they can be easily embedded in any software tool [27].

C. and Praveenkumar, in [82], developed an approach for the purpose of dynamic scheduling and applied it on a sample project. The approach considers both delayed and completed within the planned time activities, enabling rescheduling of activities not yet started. On another study Kerkhove and Vanhoucke, [83], used also an approach of performing dynamic scheduling integrating risk management (through uncertainty related to the activities and weather conditions) and project time control applying it on offshore construction projects. A previously mentioned study by Kim et al., [63], proposed a system for schedule updates from progress measurements, through the use of *Synchro* software for the 4D model, and *Microsoft Project* for project scheduling, which generates critical schedule information on activities to improve the process of decision making by project managers (Figure 27).

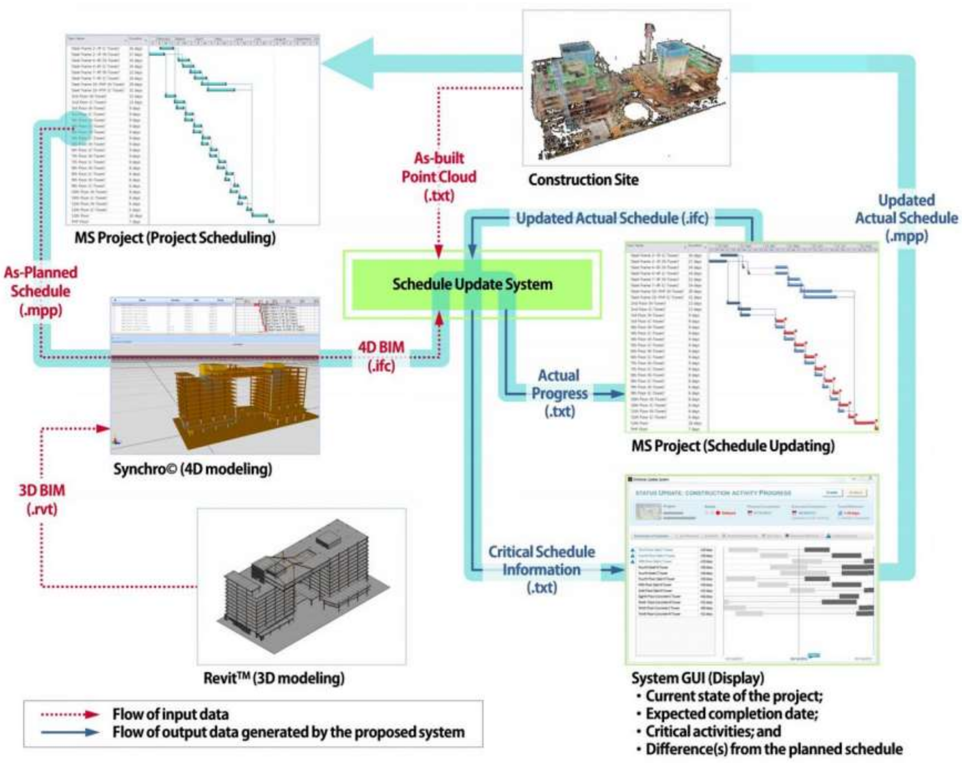


Figure 27 - Proposed system for schedule updates by Kim et al. in [63].

Despite the aforementioned research cases, Fahmy et al., states that construction project scheduling bring intrinsically complex and dynamic problems, whereas most of techniques are static or deterministic in nature [81]. On another note, Benham et al. in [84] claim that network-based scheduling methods were not originally developed for managing the production phase in construction projects, but designed for projects that are highly predictable and static (e.g. manufacturing). Hence, there is a need for optimized real-time scheduling processes to provide better resource management including manpower and cost efficiency. In a study by Fahmy et al., [81], a dynamic scheduling model to optimize schedules to manage real-time events was proposed. The dynamic scheduling model formulated based on the RCPSP[19] utilizes multi-objectives optimization of cost, time, resources, and cash flow throughout the construction phase, to overcome the problem of complexity and dynamic of construction project scheduling.

2.5 Progress Monitoring

2.5.1 Progress Quantification and Visualization

Figure 28 - IDEF0 for progress assessment.

The progress monitoring step is based on the comparison between the as-planned and as-built model. Depending on the previously mentioned techniques, from data acquisition to data processing, the progress estimation can be done in different ways.

- Comparison based on quantities of work performed (BoQs) directly from IFC/BIM model

If the as-built data gathered on site is processed into an IFC BIM model, its comparison with the as-planned model is based on the quantity take-off from the IFC elements geometry. Here, a direct volumetric comparison between as-built and as-planned models is not required since percentages of completion of elements can be obtained directly from the numerical comparison between constructed quantities extracted from both models.

Mahami et al., in [85], developed an automated construction progress monitoring using Structured-from-Motion and Multi-View-Stereo (MVS) algorithms coupled with photogrammetric principles to generate

[19] Resource-constrained project scheduling problem

the as-built point cloud. Later, the as-built BIM model is generated from this point cloud, using the boundary tracing algorithm [73] and the comparison between as-planned and as-built is done through the calculation of work quantities performed.

- Comparison based on estimation of completed elements from as-built point cloud data

The main methods for this type of progress estimation, tend to make a comparison between as-built point cloud data (obtained from laser, photogrammetry, etc.) and the as-planned BIM model in terms of proximity metrics (similar to Scan-vs-BIM explained in 2.3.1). In this case, unlike the previous method, the as-built BIM model is not generated directly from the as-built point cloud. Instead, the progress monitoring is based on the detection of objects and proximity of point cloud points to the as-planned model elements. Several methods can be used for this type of progress assessment such as ray thresholding for detection, object detection (by overlapping), enclosed volume comparison, voxel occupancy-based thresholding or bounding box generation and thresholding [34].

Omar et al., in [52], proposed an automated system to detect delays, using close-range photogrammetry for data acquisition, where after registration, the photos are used to generate the as-built point cloud at a given time, encompassing the details to detect discrepancies between the as-built and as-planned schedule, by comparing as-built point cloud with as-planned BIM model. Through a case study, the progress monitoring is achieved by creating a bounding box around each as-planned BIM model column surfaces, in order to filter and consider only the as-built point cloud points in closest proximity to each of these elements. which represent the us-built progress update for columns. The point cloud height represents the true progress of the concrete element.

On another research [36], Golparvar-Fard et al. make use of unstructured images of a construction site to create a point cloud, where the images orientation is computed using a SFM process. The image-based method for progress monitoring compares the as-planned and as-built geometry, where the scene is discretized into a voxel grid generating a volumetric reconstruction of the site. The proposed approach finds the voxels that are occupied by as-built and as-planned components and construction progress is determined in a probabilistic approach, in which the threshold parameters for detection are determined by supervised learning. In addition, it also allows to take into consideration occlusions. The progress monitoring approach relies on the discretization of space as a voxel grid to the size of a few centimetres. The outcome of the progress visualization in Figure 29, shows the behind-schedule or on-schedule IFC elements in red and green respectively. This color-coding scheme makes the accuracy of progress detection easy to observe, enabling corrections on a case-by-case basis if needed. Furthermore, an example of the progress report of the same case study is shown in Figure 30, with the percentages of completion of each activity.

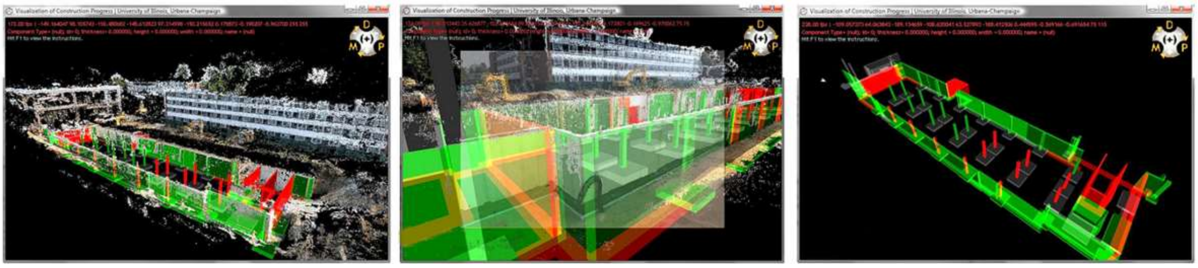


Figure 29 – Results of visualization of the outcome of the progress detection model from [36]

Visibility	progress		Scheduled Start	Scheduled Completion	Jul-08							Aug-08							Aug-08						
					28	29	30	31	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
					M	T	W	R	F	S	S	M	T	W	R	F	S	S	M	T	W	R	F	S	S
		SITE																							
		Perform Interim Survey Control and Monitor SetUp	**Aug. 6, 2008**	**Aug. 6, 2008**										X											
		RH BUILDING FOOTPRINT																							
		Install Perimeter Subsoil Drain Piping at North Wall	**Jul. 28, 2008**	**Aug. 1, 2008**	X	X	X	X	X																
		Construct Rebar Mats and Structures	**Jul. 28, 2008**	**Sep. 31, 2008**	X	X	X	X	X			X	X	X	X	X			X	X	X	X	X		
1	60%	FRPS Basement Walls and Piers[+]	**Jul. 28, 2008**	**Aug. 15, 2008**	X	X	X	X	X	X		X	X	X	X	X	?		X	X	X	X	X		
0.5	52%	FRPS Basement Perimeter Foundations[+]	**Jul. 28, 2008**	**Jul. 19, 2008**	X	X																			
		Apply Liquid Membrane at Perimeter Footings	**Jul. 28, 2008**	**Aug. 1, 2008**	X	X	X	X	X																
		Perform Elevator Drilling at NW Elevator Shaft	**Jul. 29, 2008**	**Jul. 30, 2008**		X	X																		
0	–	FPPS Basement Interior Foundations[+]	**Jul. 30, 2008**	**Aug. 5, 2008**	X	X	X	X	X			X	X												
1	86%	FPPS Interior Columns[+]	**Aug. 1, 2008**	**Aug. 8, 2008**	X	X		X	X			X	X	X											

[?] Pending owner permit the contractor was allowed to work on that nonworking day to catch up with lost progress.
[+] Critical activities in the work schedule.
[++] Visibility is the percentage of elements that are not fully occluded.

Figure 30 - Example of the progress report from the case study presented in [36] with percentages of completion of different activities.

Progress visualization is indeed relevant. The means of showing potential discrepancies between the as-planned and as-built progress is one major factor to facilitate decision making for corrective actions. According to [31] the majority of time in meetings is spent on descriptive (35%) and explanative (42%) tasks while only 12% and 11% of the time is spent on evaluative and predictive tasks respectively. The Figure 31 shows an example of progress visualization for two different points in a project developed in [17]. Based on the work schedule and the comparison performed variations are identified, colour coded, quantified based on the number of days according to the schedule finally reported. Based on the comparison between the actual and the planned costs, cost performance index and schedule performance index are assessed and presented. These two progress performance indicators are presented on the next section regarding the analysis of the progress, through the method Earned Value Analysis, which make use of percentages of completion from the progress monitoring process, to compare it to the baseline schedule and planned values to assess possible delays and cost overruns.

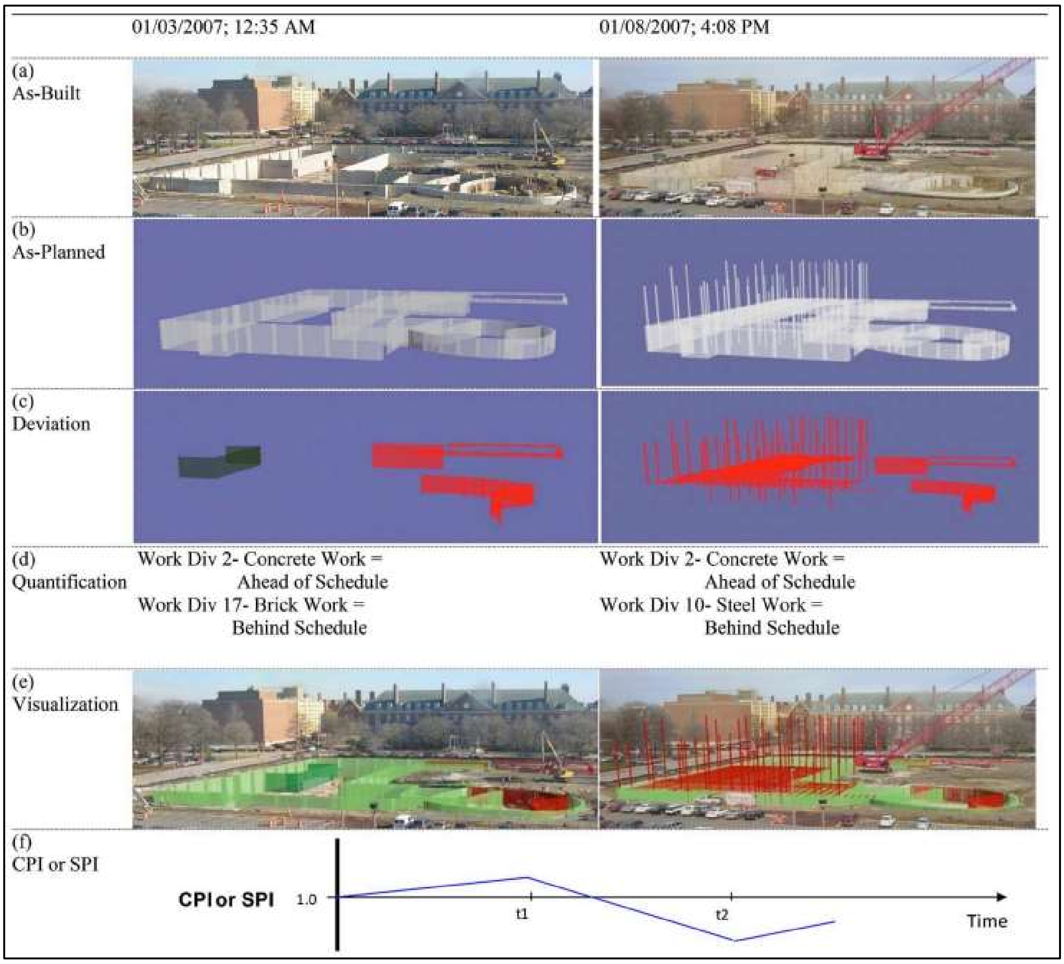


Figure 31 - Progress monitoring report from [17] with as-built photos, as-planned 4D snapshots, colour coded elements, quantification of the deviation, augmented photos and EVA performance indicators (CPI/SPI)

2.5.2 Earned Value Analysis

The project control dimension of dynamic scheduling is based in the established method of Earned Value Management (EVM). EVM is a project management known methodology to monitor the project progress and performance in an objective manner, relying on a set of straightforward metrics and performance measures to assess projects' general health, giving insight about scope, time, and cost dimension of a project's progress to date. Their purpose is the early warning about project issues or possible opportunities to be explored. It tries to answer questions about difference between project planned and actual cost, if the progress is ahead of schedule or in delay, and the expected remaining time and cost of the project.

The 5D baseline schedule can be converted into a time-phased planned value for each activity. Planned values can also be obtained for the whole project at different time intervals. The analysis of planned vs actual can then be made at different levels.

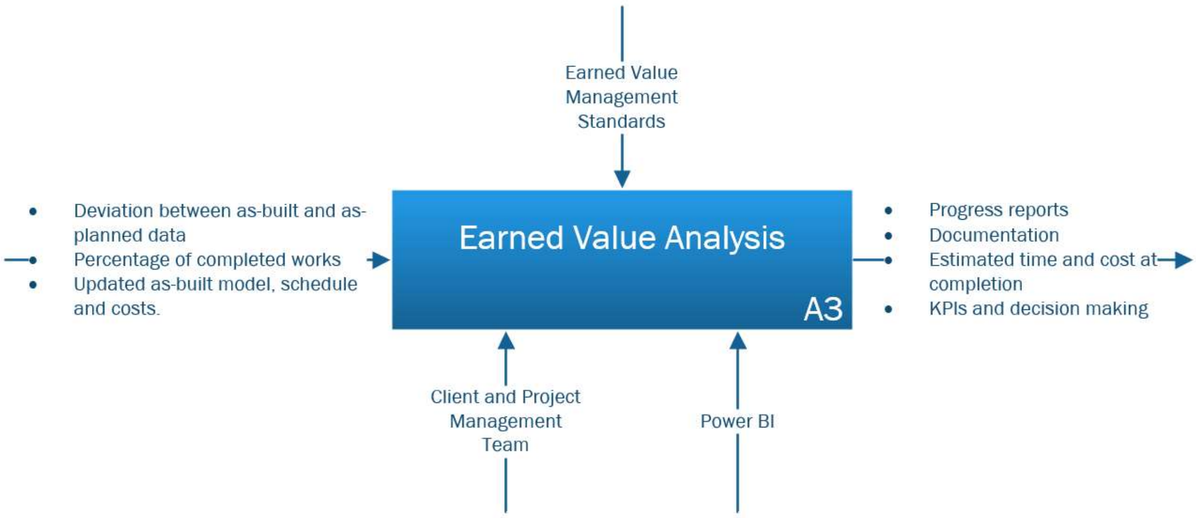


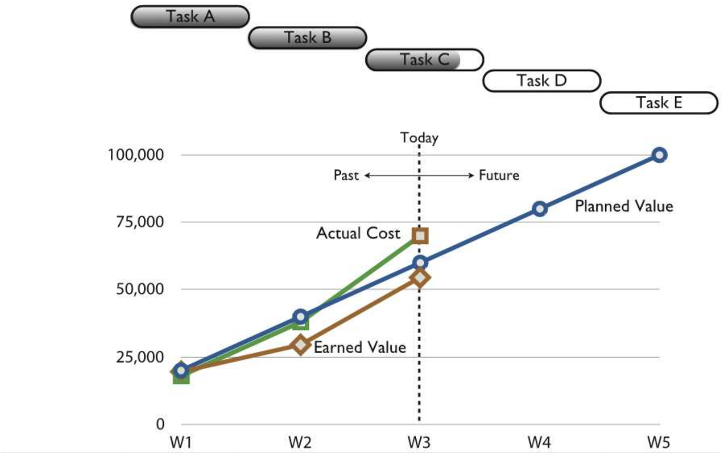
Figure 32 - IDEF0 for Earned Value Analysis.

The Earned Value Analysis (EVA) is a standard quantitative technique used in project management for monitoring and controlling purposes, with the goal to support and facilitate the project's cost control process, based on comparing the progress and budget or work packages to planned work and actual costs. According to [18] the results of this analysis are used for EVM which evaluates variances, trends and forecasts based on the EVA results. The main indicators of the Earned Value Analysis technique are:

- Earned Value (EV) - measures the progress of the project. It is the percentage of the total budget actually completed at a point in time. Also known as the budgeted cost of work performed (BCWP), it is calculated by multiplying the progress percentage by the budget for the corresponding activity or work package.
- Planned Value (PV) - the budgeted cost for the work scheduled to be done. This is the portion of the project budget planned to be spent at any given point in time (it can also be for an activity or WBS component). This is also known as the budgeted cost of work scheduled (BCWS).
- Actual Cost (AC) - refers to the cost incurred for the work performed.
- Budget at Completion (BAC) - The total approved budget when the scope of the project is completed. It is also the total planned value for the project.

The EVM uses then the following measures and indicators:

- the EVA indicators,
- variance analysis,
- trend analysis, and
- forecasting.



PV	20,000	40,000	60,000	80,000	100,000
AC	20,000	40,000	70,000		
EV	20,000	30,000	55,000		

Figure 33 - Example of planned value, actual cost and earned value at a specific time during the project [27]

With the terms PV, EV, and AC defined, key calculations can easily be performed to give important information on project progress for a certain period:

Table 2 - Earned Value Performance Indicators

Parameter	Formula	Description	Analysis
Cost variance (CV)	CV = EV – AC	Difference between what was budgeted and the actual cost of the performed works during a certain period of the project.	> 0 - under budget < 0 - over budget
Schedule variance (SV)	SV = EV – PV	Difference between the ammount of budgeted works performed and the planned works during a certain period of the project.	> 0 - ahead of schedule < 0 - behind schedule
Cost Performance Index (CPI)	CPI = EV / AC	Ratio of budgeted works performed vs the actual cost of the exact same works. The index can be used to forecast task cost using the CPI to date.	> 1 - better performance in terms of costs < 1 - worse cost performance
Schedule Performance Index (SPI)	SPI = EV / PV	Ratio of budgeted works performed vs the budgeted works planned to date. The index can be used to forecast task finishing date using the SPI to date.	> 1 - more works performed than scheduled < 1 - less works performed to date compared to schedule

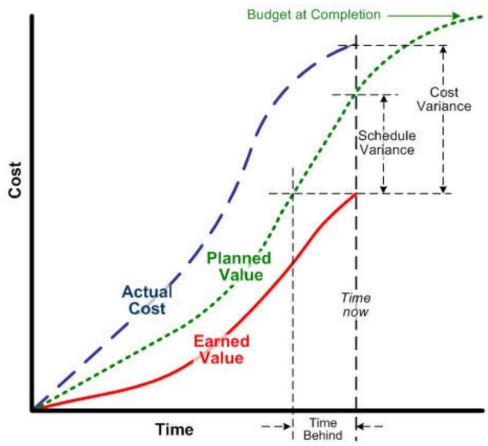


Figure 34 - Cost and Schedule variance illustrated on progress chart [86].

Since one the primary tasks of the project management team are to take action and decision about the future, through forecasting the total project cost and the time to completion. As mentioned earlier, this critical to take corrective actions when problems or opportunities arise. EVM metrics are then designed to provide forecast about the cost and time performance, based on current performance and assumptions about the future performance. Then, the estimate at completion (EAC) might diverge from the BAC based on the project performance up to date. One of the ways to calculate the EAC at a certain point of the project progress, is the forecast based on the remaining works left at the present CPI (assuming the cost performance index will remain the same until the end of the project):

- EAC = BAC / CPI

These indicators provide the project management team insight about how the current situation will affect the project and the possible delays it will cause. By warning and communicating the project performance through these indicators to all stakeholders, the decision-making process and corrective measures become clearer, and together with the progress visualization and quantification provided by BIM a better plan for action can be specified with exact targets and goals.

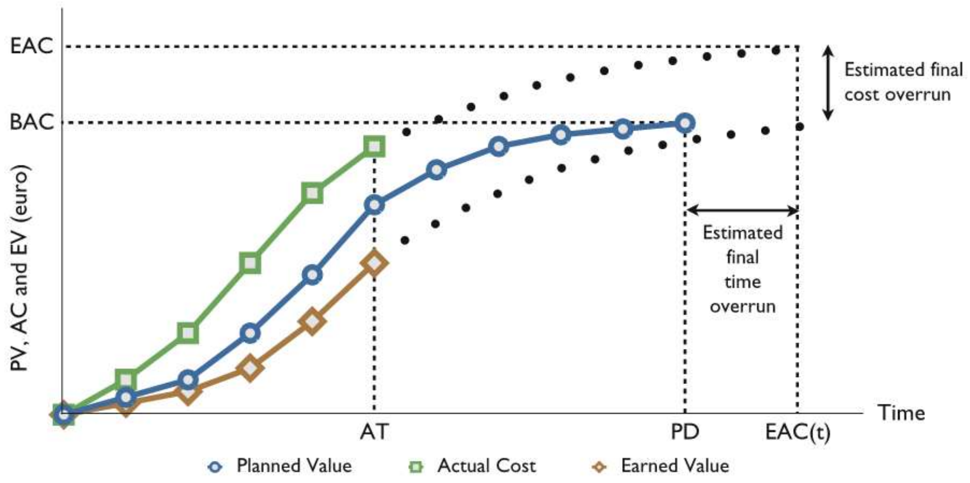


Figure 35 - Chart with planned value, earned value, and actual cost at a given time [27]. The project is performing over budget and behind

2.6 Software Tools

2.6.1 Bexel Manager

The main software presented on this case study is the Bexel Manager software, developed by Bexel Consulting with the central aim of supporting AEC project management. This open BIM platform based on advanced technologies fully integrates 3D, 4D, 5D and 6D BIM dimensions towards digital construction management workflows, configured according to the ISO 19650, enabling diverse processes automation providing project management teams with full control over their projects’ development. The upgraded efficiency that its flexible system provides for its users enables better overall decision-making using Gantt charts and Line of Balance (LOB) for a full control of the schedule.

Figure 36 - Bexel Manager platform [39].

Being an open BIM platform certified by buildingSMART international, leverages its use towards collaborative approaches supporting IFC and BCF file formats. The application merges separated IFC models creating a federated model with proprietary data structure, facilitating several processes such as review of design and data, clash detection, quantity take-off, cost estimation, schedule management and progress monitoring. It brings several advantages to simplify and improve coordination of construction management:

- All tasks created are based on BIM model elements, creating an instant relation between the model and all processes, and enabling the smart mapping of model elements to schedule tasks and cost items.
- Smart creation of selection sets and breakdown structures allowing prompt quantity take-off.
- Intelligent BIM based scheduling engine allowing advanced analysis and optimization, resource management and procurement. Detailed construction plans are automated for projects of any level of complexity with the capacity to deal with thousands of activities at the same time.
- Integration of custom cost database (e.g., Masterformat, Uniformat, etc.) or company cost database.
- Cost control through 4D/5D integration and analysis within the same software aided by the implementation of cost versions and classification (Cost breakdown structures).
- Real-time progress monitoring and reporting, through schedule comparison between planned and actual progress
- Power BI integration for different analysis allowing better understanding and communication between stakeholders regarding business analytics such as Earned Value Analysis.

- Open API leveraging automation and allowing user to execute different commands and scripts such as data enrichment of the IFC models with information created on Bexel.

The baseline schedule intelligently linked with BIM model elements and embedded cost information enables the management of all progress process. The elements that are being executed during the construction process can be registered in the 5D model according to their progress. These updates in the system allow for tracking of cumulative costs over time and if the project is progressing as planned. The visualization of model-based Gantt charts, Lines of balance and histograms of materials, labour, and equipment provide the project managers with all information for an efficient progress monitoring, facilitating activities such as resource management.

Bexel Manager ultimately enables a single source of truth with all data and information related to any project, interconnecting scope, model elements geometry and metadata, works schedule planning and costs. The integration of all these components allows for an automated workflow where the occurrence of any change in one of the dimensions automatically updates the remaining ones. The comprehensive applications of Bexel improve project efficiency by significantly reducing risks and enhancing planning of project activities and resources, increasing profit margins and leveraging lean BIM management approaches, empowering project managers and clients with time to make wiser decisions.

3 FRAMEWORK

After the literature review regarding the several topics of advanced progress management, a framework for the case study developed on the next chapter is proposed. This framework builds upon the use of IFC for the federated model on an openBIM environment, the use of BCF manager for exchange of information and *Bexel Manager* advanced features to process the progress assessment of the project. The framework introduced provides a workflow to be adopted during the construction phase, when the works on site have started and information for progress control can be gathered.

For a solid and useful application of the workflow here developed, IFC models from different disciplines must contain essential information required for the progress monitoring at the elements level. Therefore, in the earlier stages of the project, the design team develops the BIM model considering its use for the construction phase, having in mind breakdown structures, quantity take-offs and classification of model elements. This pre-process enables further integration of BIM elements with cost information (including resources) and schedule activities, through well-defined work breakdown structures. The attribution of WBS and Classification Systems (e.g., Uniformat) codes to the model elements enables their linkage with activities within the Gantt chart allowing the project management team to visualize the construction process simulation (4D) enriched with cost information allowing the cash flow control (5D).

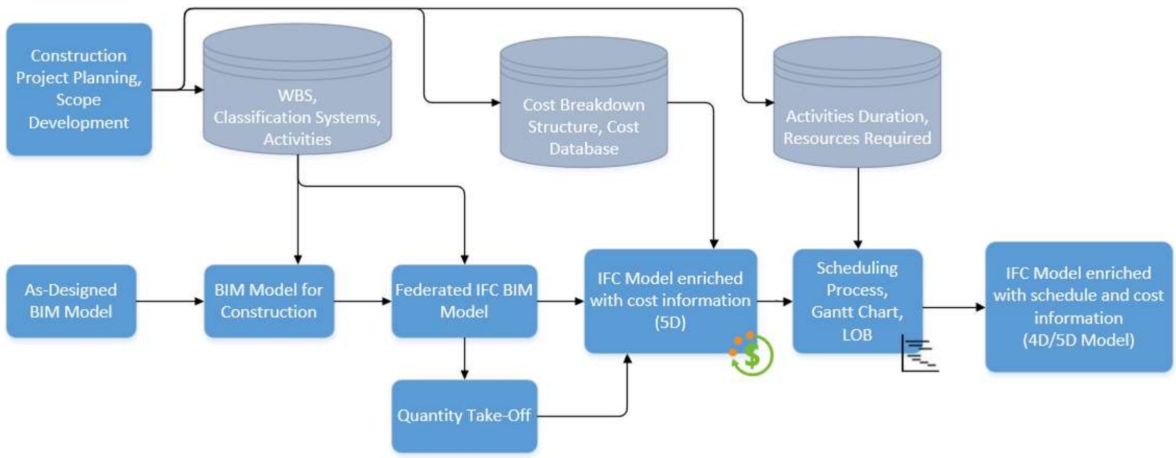


Figure 37 - Pre-process of model data enrichment with construction planning information regarding WBS, cost and schedule (4D and 5D BIM) for progress management.

After achieving the final As-Planned model the process of construction progress monitoring will take it as a starting point, and further comparison will be made against the planned schedule and costs throughout the construction phase.

An efficient construction progress relies significantly on the continuity of works completed and performed as per planned, which can only be affected by uncertainty relative to the different activities. Therefore, it becomes important to understand what causes the non-completion or delays of activities.

According to [87], several preconditions have to be fulfilled prior to the start of any activity. These preconditions are also the main causes for activities' delays and are broken down as follows:

- Construction design and management.
- Components and materials.
- Manpower productivity.
- Equipment and machinery.
- Sufficient space so that the task can be executed.
- Connecting works, progress of predecessor activities.
- Climate conditions.
- Safe working conditions.
- Known working conditions.

All previous items reflect possibilities of components where unexpected (or sometimes expected) events may incur delays. The progress monitoring case study departs once the construction has already started and make use of types of delays related to the abovementioned factors to conduct the delay and earned value analysis.

3.1 Proposed Workflow

As mentioned before, the progress management is an essential and mandatory process during the construction phase that evaluates the progress (on a weekly or monthly basis) towards the project performance target based on delay and earned value analysis. It also ensures the contractual requirements are being achieved and ultimately generates and validates payment certificates, being useful for all involved parties.

The workflow is shown in Figure 38 and it considers the following stages:

- From the As-Planned IFC model, regular monthly look-ahead plans are made with information regarding the works planned for each month in *Bexel Manager*. This information is exchanged through BCF format (supported by *Bexel*) files with the site management team.
- The advantage of using the BCF Manager is that it can work with several BIM viewer platforms in an openBIM environment. This enables the team on site to view the planned works (in the BIM viewer or *Bexel Manager*), develop a plan for photographic acquisition on site of the monthly progress and exchange back to the project management team the input of actual progress information (contemplating completed elements of works performed, percentages of completion and information on used resources).
- The BCF file with data and progress information sent back to the project management team is imported and launched in *Bexel*. The information regarding works completed and in progress,

resources, and delayed and postponed works is introduced in the model is reviewed and validated by the PM team by comparing it with photographic register of performed works shared by the site management team. If the information is coherent and clear the progress assessment is carried out.

- When entering the progress information in the software, the project schedule and costs of construction are automatically updated through the advanced features of *Bexel*, creating a new schedule based on actual performed works. This new schedule can be further compared with the planned schedule since the system has the capacity of keeping record of previously defined schedules.
- The project control is carried out by comparing the actual vs planned and the progress analysis is performed in terms of EVA and KPIs, providing a consistent evaluation of the project performance. Additionally, the progress reports, valuation and payment certificates are explored and generated in *Bexel Manager*, to close out the monthly progress task.

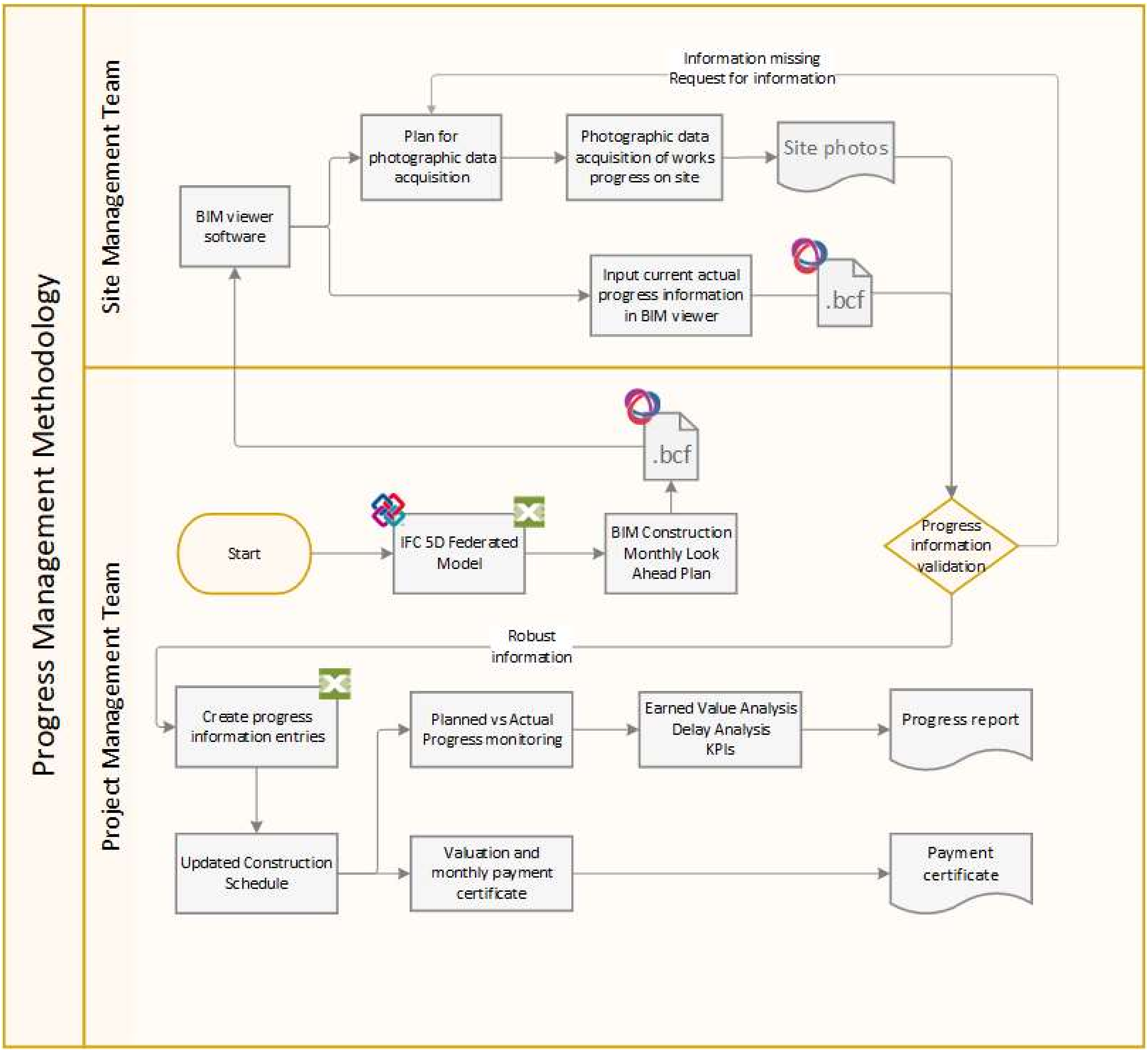


Figure 38 - Proposed Progress Management Methodology.

4 CASE STUDY

In this section the proposed workflow for progress management during the construction phase is applied on a fictitious case study of a sample project consisting of a three-story building which will be used to illustrate the procedures for a real case scenario. Some assumptions are set based on real life circumstances to test the workflow in the *Bexel Manager* software from a project management point of view, and within established boundaries of the research purpose. As it will be presented, the process provides the accessibility and transparency of information meaning simplified calculations and model updates, bringing added value in monitoring the construction not only for the contractor or project manager, but also for the investor due to the clear insight of financial resources and the project status.

4.1 Breakdown Structures for Progress Monitoring

The preparation for the project construction progress management starts at design stages developing the model according to defined information need. In *Bexel Manager* an integrated system is created with breakdown structures, cost management and 4D and 5D scheduling, mapping all information with the BIM model. Since the focus is to study the progress itself, these pre-required steps were defined prior to the progress management task and are only generally illustrated here according to the Figure 37, providing only context to the core of the framework.

It is of upmost importance to define and breakdown the schedule and cost items according to the work breakdown structures (WBS). In addition, the location breakdown structure (LBS), is also applied on the model preparation phase, and activities are not only divided into work groups but also in implementation locations. All elements in the model are associated with levels/building stories and with construction sequence. The latter is related to a horizontal subdivision of zones, where elements within the same level are subdivided in three phases, arranging the sequence of works in Phases 1, 2 or 3.

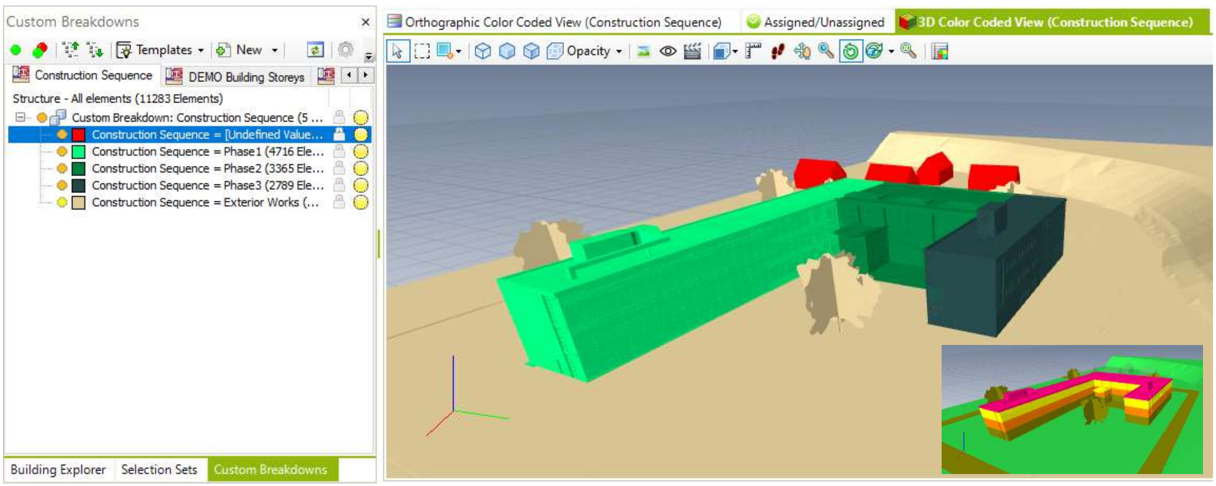


Figure 39 - Location Breakdown Structure of the model in *Bexel Manager*.

The work breakdown structure defined is associated to the BIM model at the elements level by creating parameters which are populated with the corresponding codes of the work packages from the WBS. The schedule and cost structures and broken down by the WBS and LBS. In the case of the scope of this project, the breakdown structure of works is made based on the classification system Uniformat. This classification system arranges data about the construction project physical parts by function.

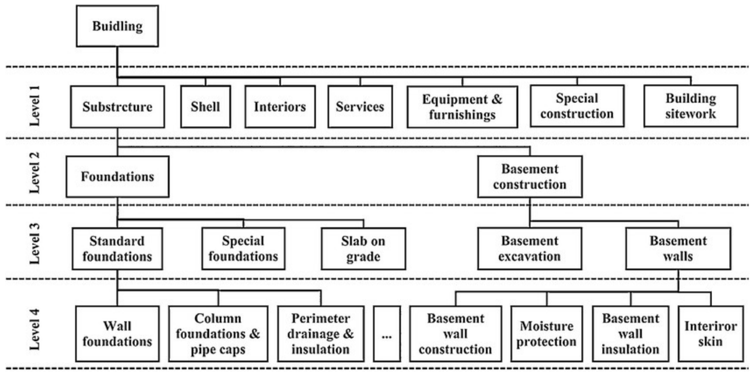


Figure 40 - Uniformat Classification for WBS [88].

In *Bexel* the quantity take-off is carried out based on this structure breakdown (Figure 41). Once concluded, the cost breakdown structure (CBS) is defined at the activities level of each work item. Here, it is necessary to decide how to define the detail required for monitoring of cost items (more subdivision means more detailed control of the progress at the element level). In short, cost items represent activities associated with costs. These activities are broken down within the work items, based on the Masterformat code and automatically linked to each element. The construction of an element is finished when all its related activities are completed.

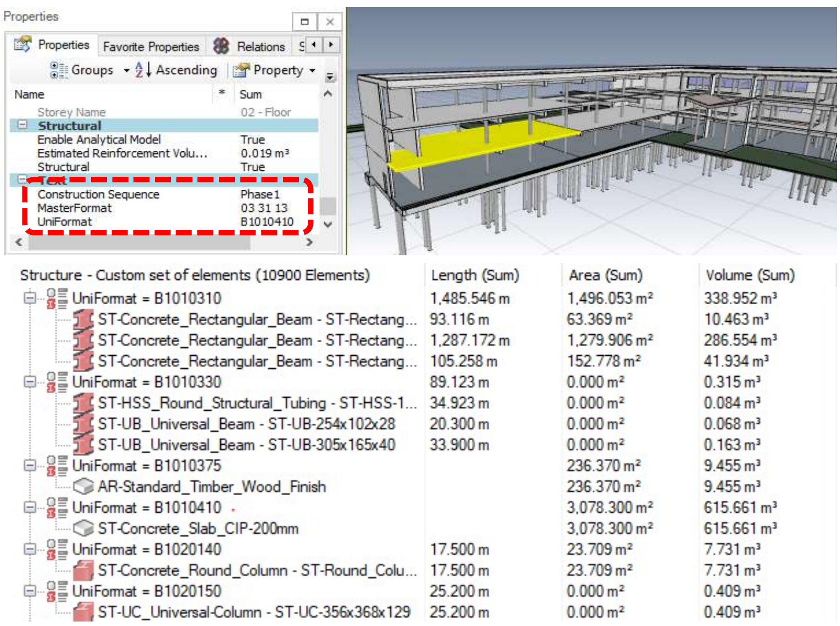


Figure 41 - Elements Uniformat classification and QTO in *Bexel Manager*.

Furthermore, the Masterformat approaches classification from the perspective of materials. This level of detail is important for an efficient progress monitoring as it provides control at the elements' layers level (associated with activities). This can be illustrated with the example of the concrete columns, where activities are subdivided in formwork, reinforcement, concrete pouring and finishing through the Masterformat codes providing the project manager with control on the level of implementation costs and resources (manpower, material, equipment, etc.) defining unitary costs for the different elements' activities (Figure 42). All cost items are finally automatically generated and linked to the building elements, which by combination with the QTO generate the total cost of the project.

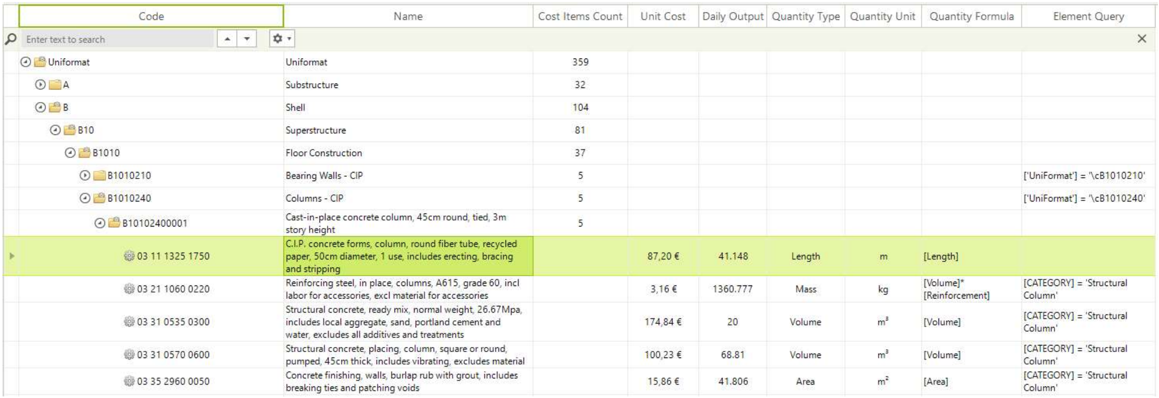


Figure 42 - Cost breakdown structure based on WBS. Each classification/ work item corresponds to a Uniformat code and each activity his coded based on the Masterformat classification. Also, each activity has a unit cost, quantity type and formula attached so that the cost of building a certain element can be broke down in smaller parts (cost items).

The integration of different data and established relations, provides the connection between the model and associated quantities, cost items, or resources, enabling the creation of bills of quantities and the future optimization of the schedule (Figure 43).

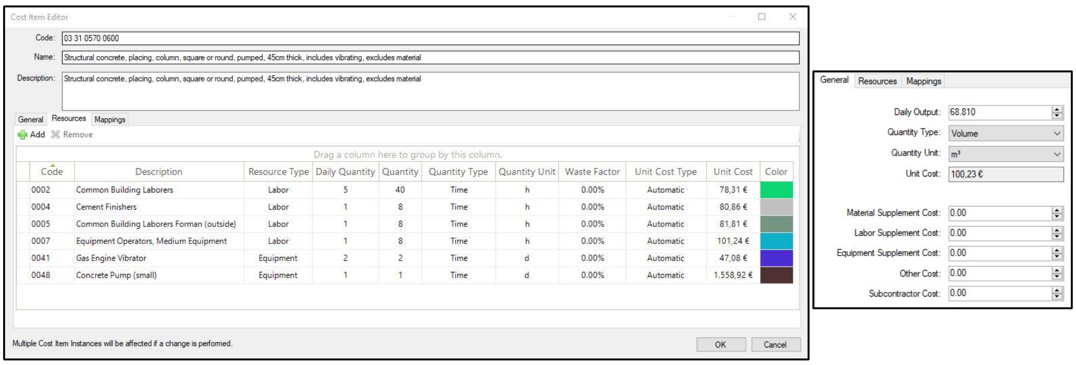


Figure 43 – Resources costs and quantities assigned to activities in *Bexel Manager*.

This level of information at the activity level enables the change of daily output quantities and required resources. The integration of this information with the schedule allows it to be automatically updated, supporting the construction planning by minimizing the number of steps and time to process schedule changes as well as the progress monitoring, since a comprehensive insight can be provided regarding resources used, delays, cost variances, etc.

Bexel Manager provides a powerful scheduling generation, where the methodologies and zones are used to simplify and automate the process of generating construction sequencing integrating 4D and 5D dimensions, by merging methodologies and zones.

The zones represent the spatial distribution of works and contemplate the building levels (vertical subdivision is the distribution of levels/storeys in the vertical axis defining a logical construction sequence from the lowest to the highest level, in this case, sub level, 3 floors and the roof, Figure 39) and phases as previously mentioned (horizontal hierarchical subdivision, in this case study, the model elements in the horizontal axis are subdivided in 3 building phases and exterior areas).

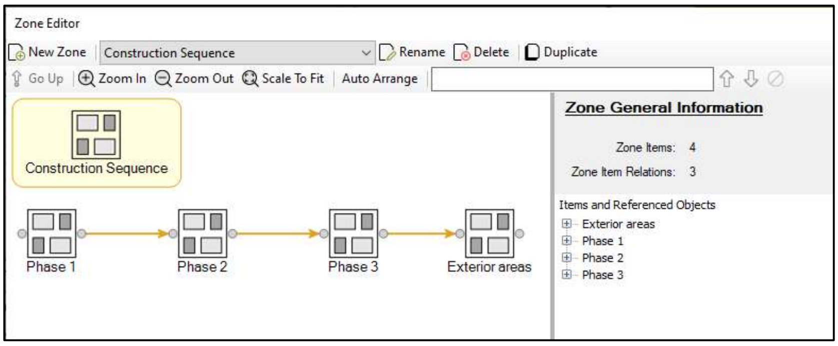


Figure 44 - Building zones defined by construction sequencing.

The methodologies are defined based on the CBS and construction logical sequencing of works. It is a more complex process than zones sequencing due to the nature of works. This automated process enables the quick generation of Gantt chart and Line of Balance (LOB) and further 4D and 5D construction simulation since everything is connected to the model elements. This task takes into account the construction process technology, organization of the construction site, contractor's resources and timeframe defined by the investors/clients.

The methodology created for this case study baseline schedule was based on the two complementary classification levels as defined on the CBS. Uniformat for the main work items and packages (e.g., from Substructure to Pile Caps family types levels, Figure 45) and Masterformat for the activities (which as previously mentioned are material-based work item segregation, e.g., "03 21 Reinforcement", Figure 46). These work groups are linked by defining the nature of the relationships between each construction item (e.g., finish-start), on a logical sequence of works (e.g., finish-start).

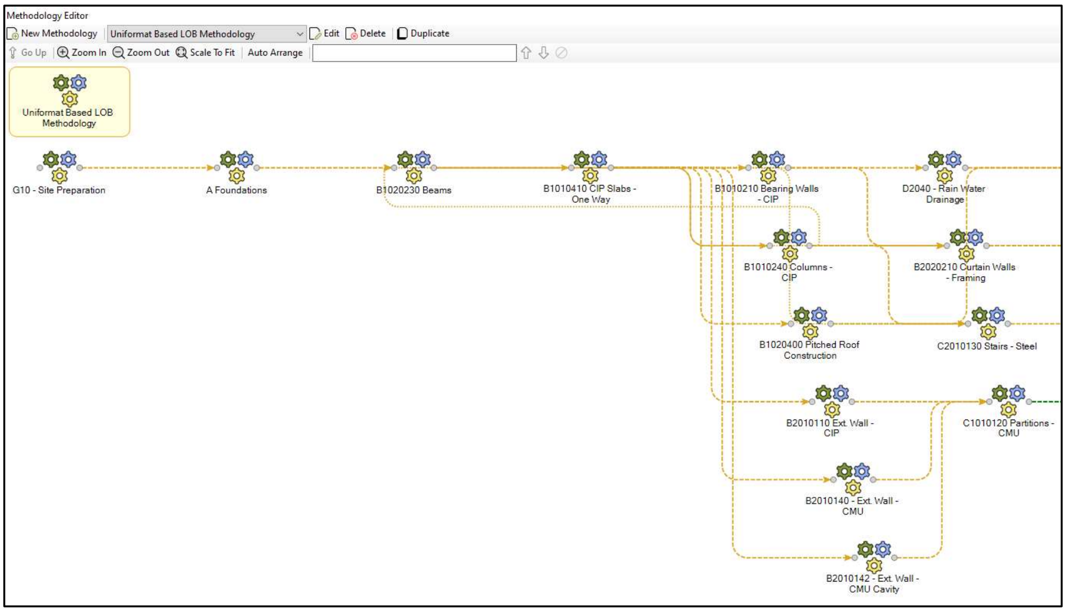


Figure 45 - Methodology for scheduling creation according to Uniformat classification.

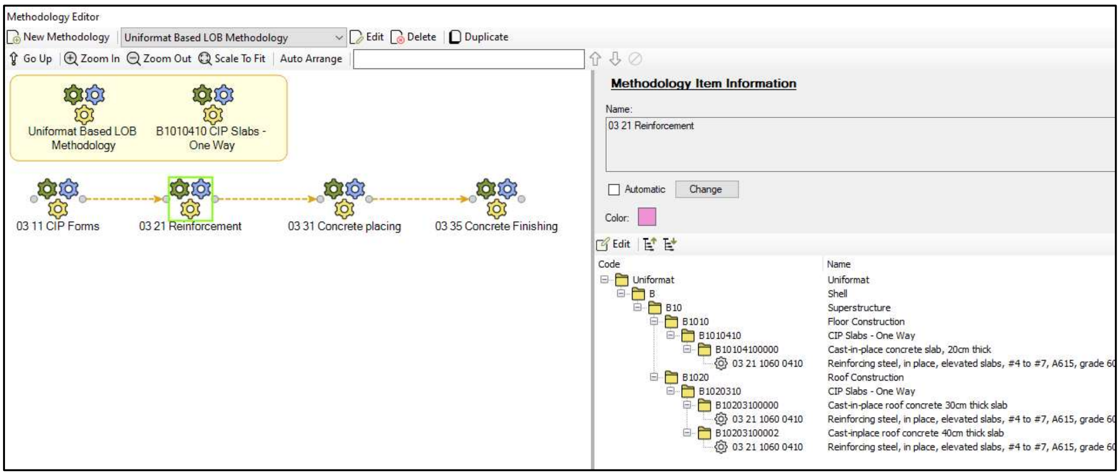


Figure 46 - Methodology for activities within the same element classification. In this case, cast-in-place slab works are subdivided formwork, reinforcement, concrete pouring, and finishing.

This process illustrates the advantage of *Bexel Manager* when it comes to create a schedule where a large number of repeated activities is foreseen, such as the construction of a high-rise building, where activities are repeated through individual floors, or long infrastructure buildings, where work is repeated throughout stations. The cost classification based on elements classification is also beneficial for the application of the same methodology in different projects of the same nature, leveraging a standardized way of producing schedules minimizing the effort and time spent on a task that is normally time-consuming and very demanding.

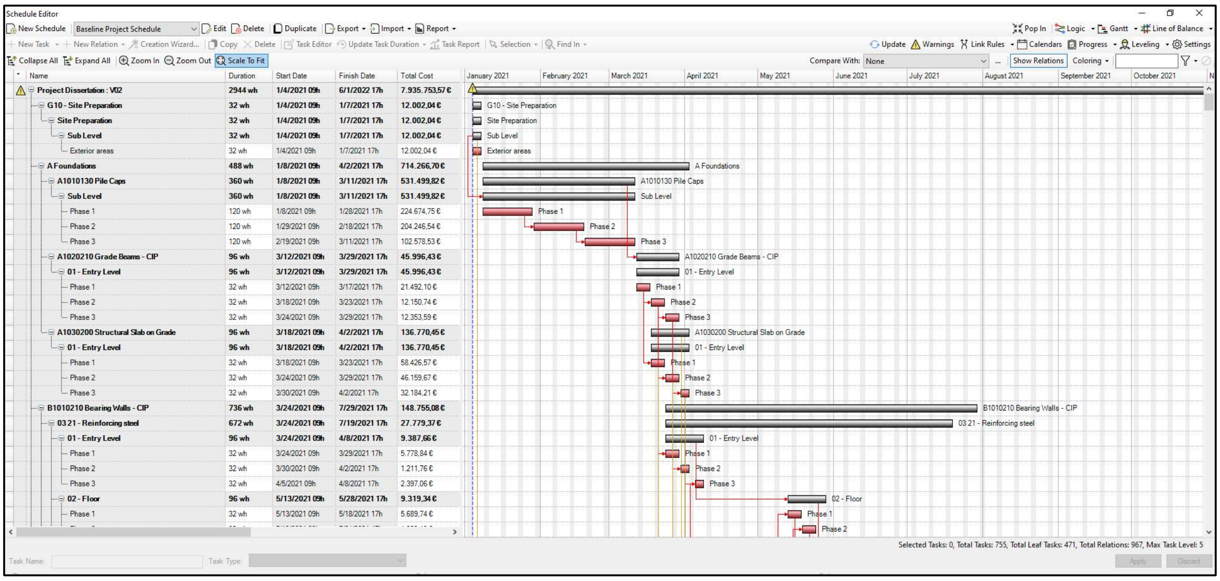


Figure 47 - Project baseline schedule from *Bexel Manager*.

Costs and durations can be assessed at activity or work packages level, providing detailed insight on the schedule in the form of monthly reports consisting of planned tasks, manpower, material, equipment, and work quantities, providing insight for the process of schedule optimization, achieving the final optimized Planned baseline schedule.

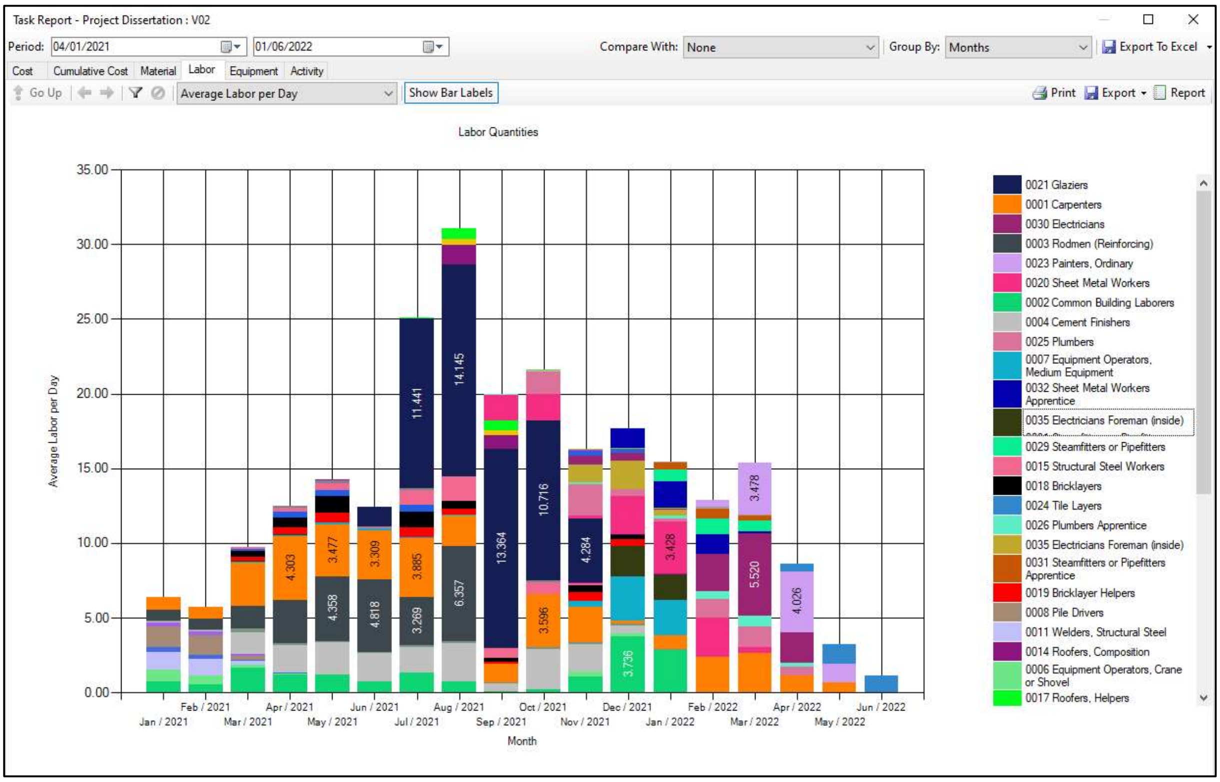


Figure 48 - Report of labour distribution by functions within the construction phase divided by month.

Finally, everything is integrated in one single platform where planning, visualization and monitoring are performed through reliable and up-to-date flow of information facilitating the progress management process leveraging its accuracy and efficiency.

4.2 Progress Management

Having the model populated with required parameters which enabled the work and cost classification as well as the scheduling process based on BIM elements, this section makes use of all these information to illustrate the progress management process considering effects of non-planned events and costs at in the overall project, through delay and earned value analysis. *Bexel Manager* key functionalities used for this study are:

- Progress entry from data collected on site and changes management.
- Cost management and intelligent scheduling.
- Model visualizations and planned vs actual analysis.
- Creation of progress Power BI reports.

As mentioned in the previous chapter delays can occur due to different types of changes to the construction plan. These can be expected or unexpected. Some of the main changes during construction can be related to poor schedule, non-feasibility of selected construction methods, site conditions, future costs reduction or increase, unforeseen ground conditions, weather conditions, labour productivity, resources prices inflation, reworks, etc. Corrective measures are taken under change management system which account for consequence of changes to schedule, cost, or project scope.

Bexel Manager provides the freedom of manage progress data in different ways. This is highly due to the capacity of creating different schedules for the same project, enabling the comparison between actual progress where the project manager can handle data according to changes to the initial baseline schedule. The first step in this process is to duplicate the initial as-planned schedule (Figure 47) to create the actual progress schedule where the progress entries will be done, setting the former as the baseline. Both schedules can be seen and compared one over the other by tasks. The straight Gantt chart bars above represent the baseline schedule while the ones under are the updated actual schedule bars allowing an easy visualization of progress of works compared to what was planned for each activity and the project in general.

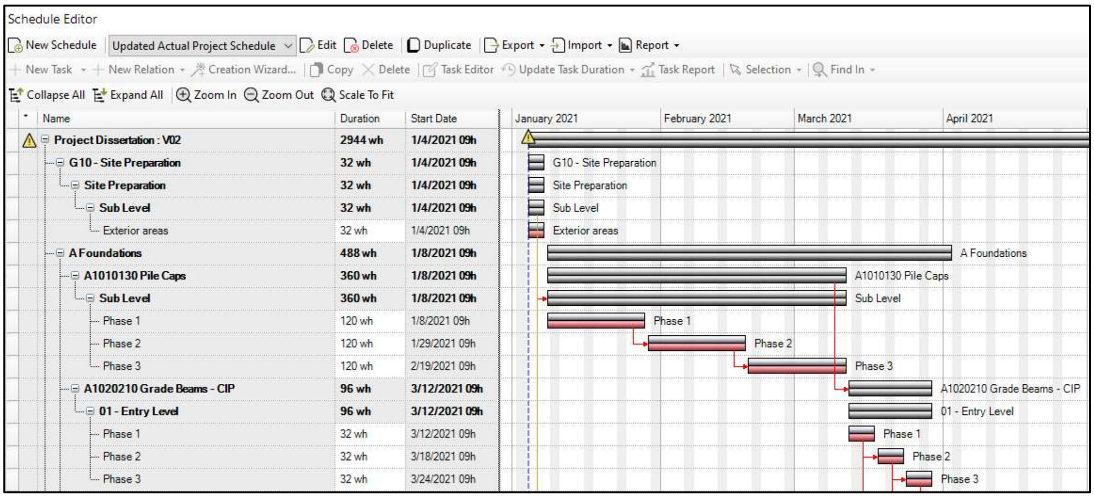


Figure 49 - Baseline vs actual progress schedule in *Bexel Manager*. Bars in red represent the activities of the actual progress schedule. Bars in lighter grey represent the baseline schedule.

4.2.1 Look-Ahead Plans

During construction phase of the case study the look-ahead plans are set on monthly periods. They set the basis for the management of tasks planned to be performed in the near future, to make tasks ready and to coordinate teams in order to achieve the initial plan. In *Bexel Manager* look-ahead plans were firstly created by making use of the construction simulation feature of the software, where by setting the monthly period interval for the animation, it is possible to select the elements that were completed within the corresponding month grouping them in selection sets. This set of BIM model elements are easily visualized allowing a better comprehension of the works to be performed in the construction site.

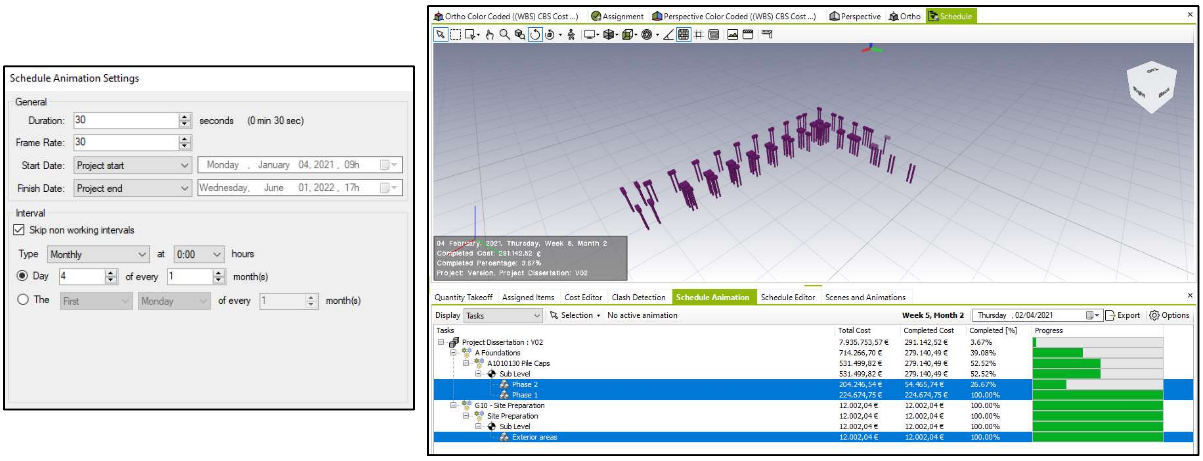


Figure 50 - 5D Construction progress simulation.

In Figure 50, on the left is displayed the start and finish date of the project as well as the monthly interval for works performed set for 5D construction simulation. On the right the works in progress and completed within the 1st month.

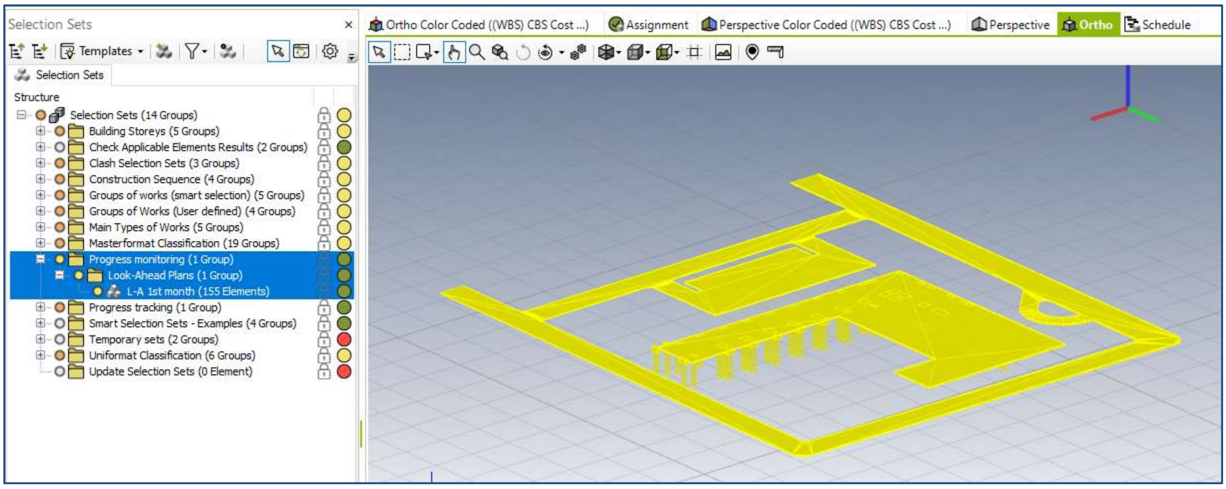


Figure 51 - Look-Ahead Plan for the 1st month.

In Figure 51 is shown the planned construction elements to be fully completed within the 1st month. The selection set created can be shared with other teams through BCF file, enabling the coordination between site management and project management teams.

This method of creation of look-ahead plans benefits from the flexibility of elements selection in case the manager wants to add or take out constructive components while getting the support from the construction simulation, being able to spot possible incongruences or mistakes to the plan sequence.

A more expedite way to create a larger set of monthly of look-ahead selection set plans relies on the API functionality in *Bexel* which was used to run a script to define all look-ahead selection sets for certain defined input of number of months. In this case it was performed for the first six months.

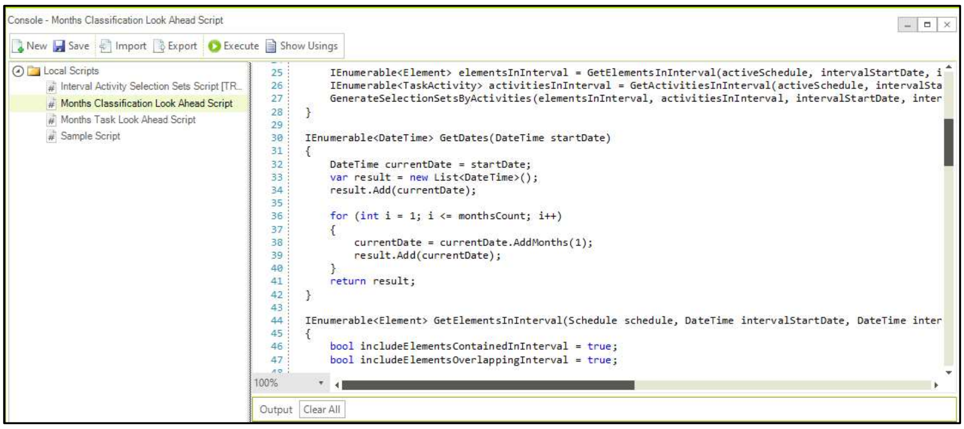


Figure 52 - Bexel Manager API console. Monthly look-ahead plans script.

4.2.2 Progress Entries and Schedule/Costs Updates

The construction starts with excavations and preparation of the site in exterior areas, followed by pilling and foundations. The first delay in the project occurs by the time the slab on grade is to be built.

Delay input directly on schedule

One of the common events that can affect the progress in construction are soil conditions, which due to the environment can cause the slab to present uneven moisture and temperature dispersal during curing and in consequence a curling effect takes place where some parts of the slab dry and shrink faster than others causing deformations along the element. The placement of the slab on grade is then delayed by one week by decision of the contractor during the construction, which is immediately communicated to the project management team which introduces this delay directly in the actual schedule. The project considers 8 working hours on weekdays, making a full week to be of 40 working hours. The introduction of this delay is done by the lag input between the slab on grade's predecessor task (grade beams) and its start (first activity of formwork installation) as shown below.

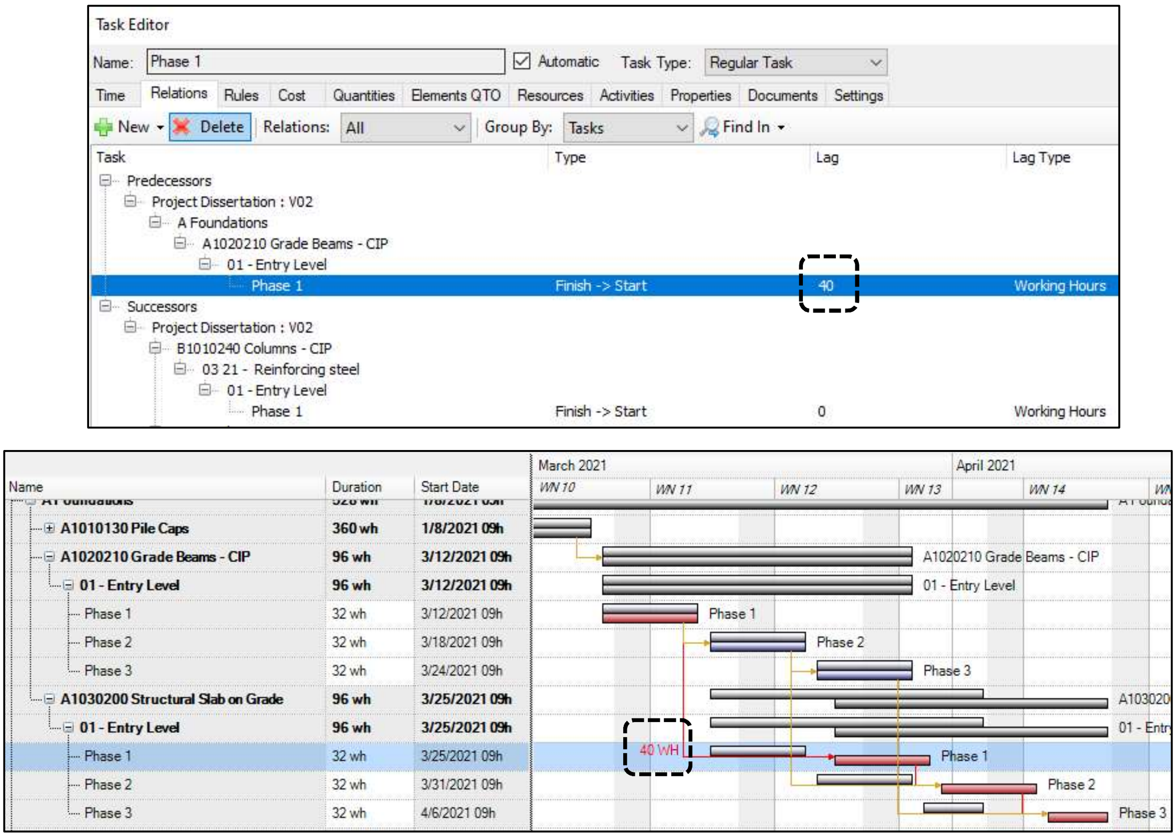


Figure 53 - Delay input directly on schedule at the slab on grade start level.

As observed, the delay affects the following tasks by postponing them. The visual comparison with the baseline schedule bars enable the analysis of the lag between planned and actual construction.

A second delay occurs during the slab curing. Weather conditions such as rain and high humidity can enlarge the duration of concrete curing which leads to the postponement of subsequent work dependent on it. This delay be inserted in the schedule in two ways - the increase of the slab on grade phase 1 task duration or by setting a lag for the next task.

Increasing the total duration of the task might incur in inaccuracies. Since the slab on grade task in the schedule comprises several different activities related to its construction (from formwork and gravel fill to concrete finishing), which means there is no control over the activity's duration but only over the slab on grade work construction as a whole, the duration increase will also increase proportionally each of the activity's duration. This means that resources will be redistributed per day which is not the reality (may lead to imprecise optimizations in case of resources levelling for example) since the extension of the slab on grade work package span is only related to curing waiting time which does not require any resources. Therefore, the second option was taken, and a lag of 2 days (16 working hours) was created between the slab on grade phase 1 and its successor tasks that depend on the slab cure (e.g., structural framing on top of the slab).

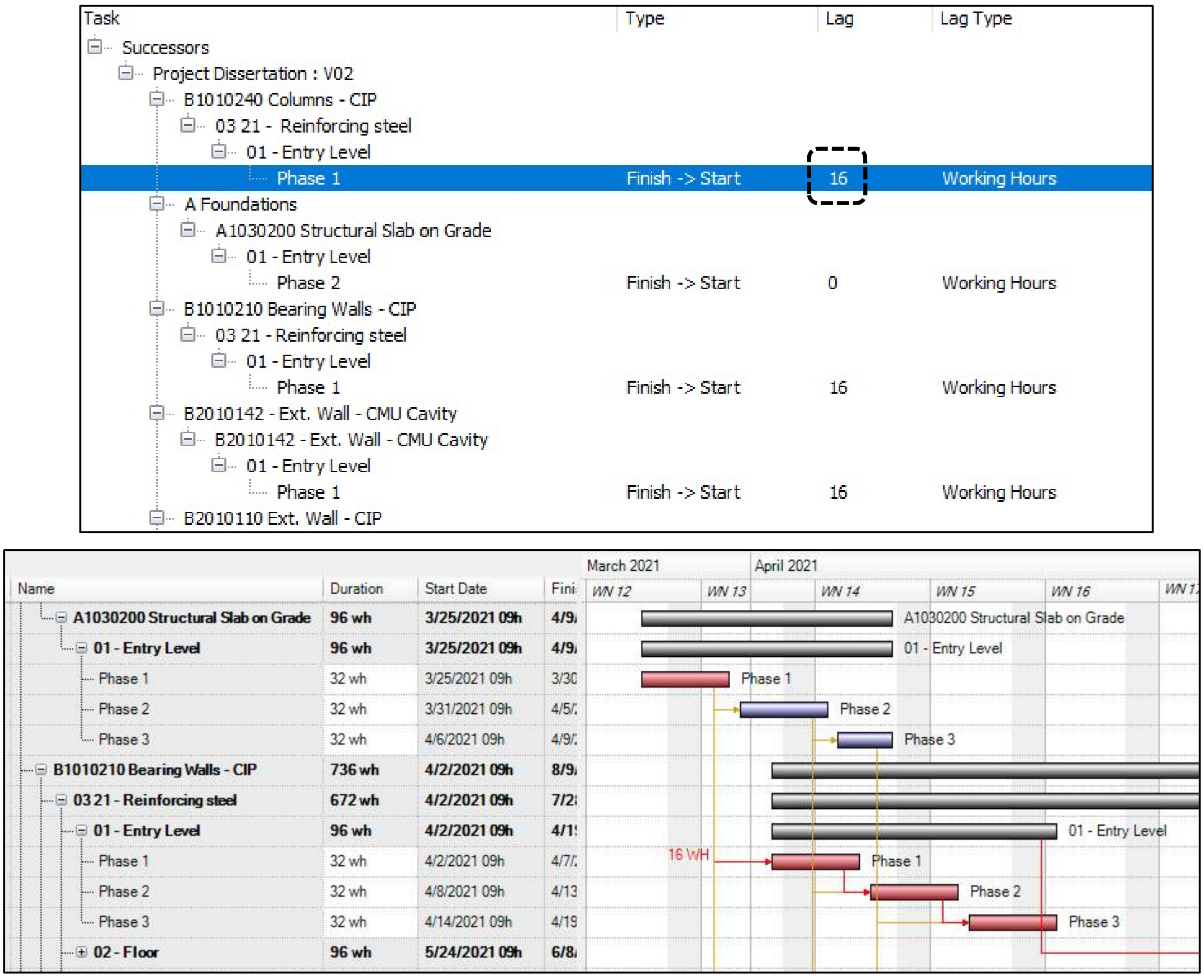


Figure 54 - Works to be performed after slab on grade cure postponed by lag input.

In the end of these procedures a comparison can be made by comparing the actual project completion against the panned. As shown below, the left represents the actual progress of works by the end of the third month and on the right the works planned for the same period. There is a clear delay on the slab on grade schedule which afects the rest of the project since it is part of the critical tasks of the construction process leading to an extension of the overall project.

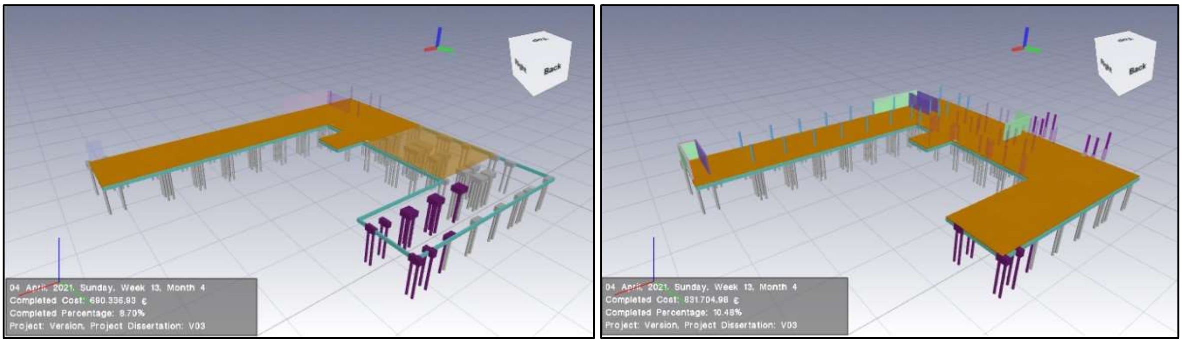


Figure 55 - Schedule animation comparison of as-built (left) vs as-planned (right) after 3 months.

Regular monthly progress entries – Executed works

As stated previously, for a more detailed progress control and following the workflow presented, the progress assessment is done on a monthly basis where the communication between project management team and site management team works as follows:

The previously created look-ahead plans with selection sets of the elements meant to be completed by the end of each month along with other relevant information are shared with the site team. The management team on site access the information and review the model containing the look-ahead plan and assess the works performed making a progress report in the form of BCF entries with elements that represent actually executed works. This information is sent back to the project management team where the progress entry is reviewed, validated, and entered. Once the progress data is added in *Bexel Manager*, the schedule is updated together with deviations from the plan in terms of costs, resources, or quantities. Finally, all changes are immediately reflected in respective cost and quantity information.

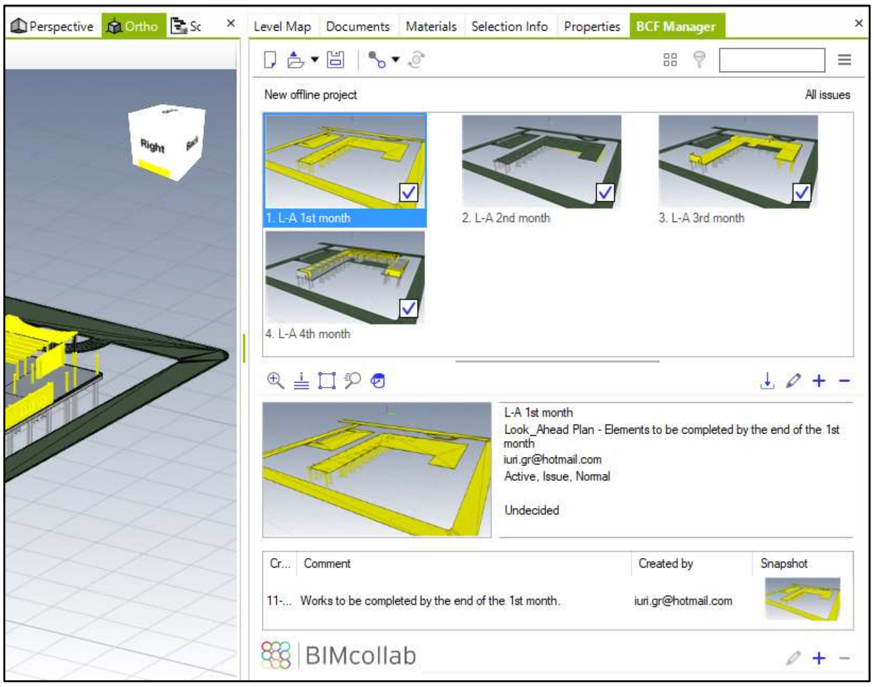


Figure 56 - Creation of BCF files with monthly look-ahead plan of works to be shared with construction site.

The process done on site can be achieved with BIM viewers that support BCF format. For the present study the *Bexel Manager* Online Viewer is put into practice. It can be used also in mobile devices such as tablets or mobile phones which provides even larger freedom of use on site. The project can be reviewed and BCF files can be loaded with the previously saved look-ahead plans. These information and groups of elements are used as the guideline to check and manage the progress of the monthly construction works. The site team updates the selection set of the monthly works by marking or selecting the actual executed elements.

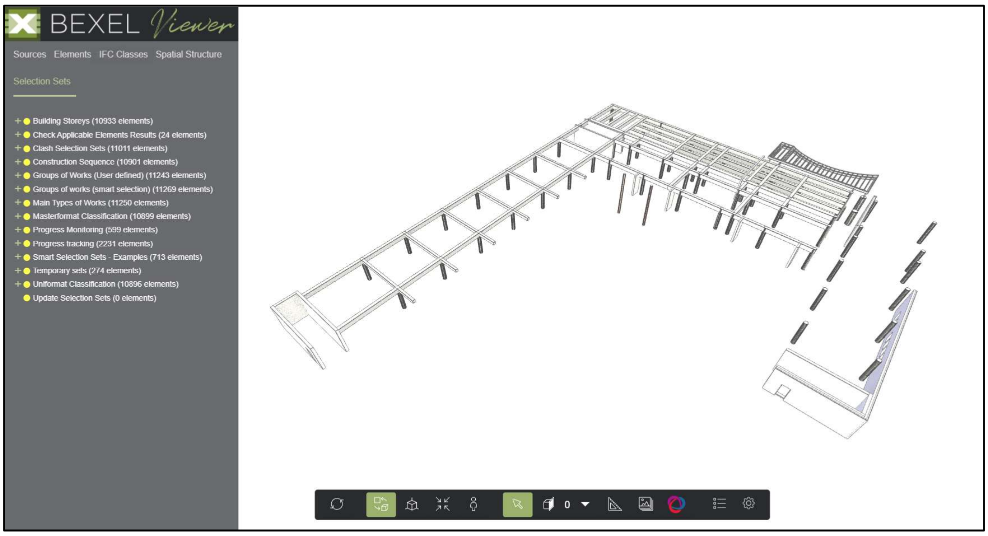


Figure 57 - Planned works to be completed during the 4th month according to baseline schedule in *Bexel Manager* BIM Online viewer.

In Figure 57 are illustrated the elements to be completed during the 4 month of the project according to the baseline schedule. The progress on site happens regularly or almost in every project, with delays. As shown previously, the project suffered a delay due to the slab on grade works, leading to the deviation between he updated actual schedule (after the delay introduction) and the baseline planned schedule (Figure 53Figure 55). In consequence, due to these delays, in the actual schedule some elements that are meant to finish in the 3rd month according to the baseline schedule are shifted to the 4th month. Therefore, the look-ahead plan of works should contemplate information from both updated actual progress schedule and planned baseline schedule, combining elements to be completed during the 4th month of both schedules. It is important to assess both schedules since the progress of works on site can either improve in a way that they can eventually catch up with delays and achieve the initial plan (or part of it) or getting more delayed due to diverse factors.

Finally, the same procedure was used for the rest of the months of the project after each progress entry. In *Bexel Manager* the project management team then creates a look-ahead selection set with actual schedule and planned schedule elements for the 4th month and share it with the site management through the BCF Manager.

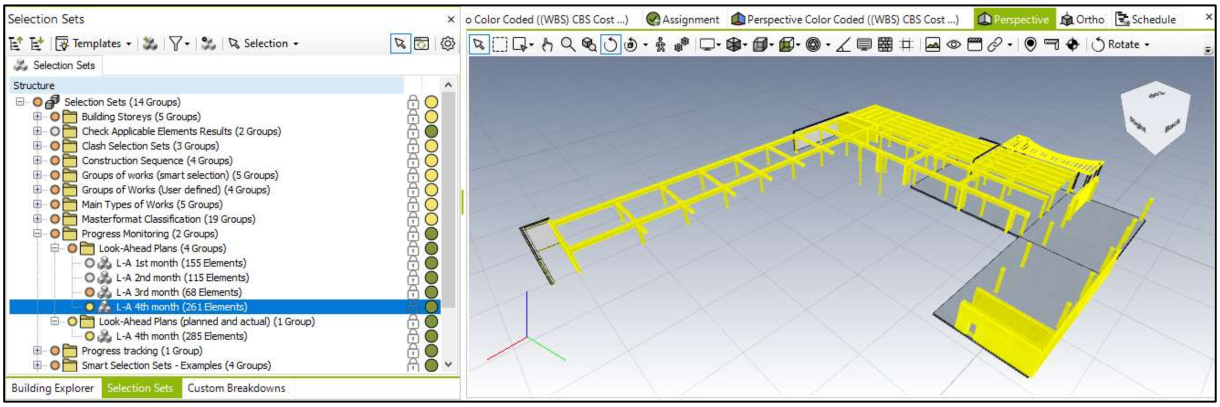


Figure 58 - Updated look-ahead plan for the 4th month. All visible elements are included in the plan. Selected yellow elements are the initially planned. Elements in grey are the elements in delay and shifted from the 3rd month.

On site, the site management team select the elements that were actually built by simply add the BCF file in the viewer and assess completed elements on site. The selected elements in Figure 59 in yellow represent the works completed during the 4th month. The site management team saves this selection and transfers it to a BCF file. Additional information can be added in the comments section.

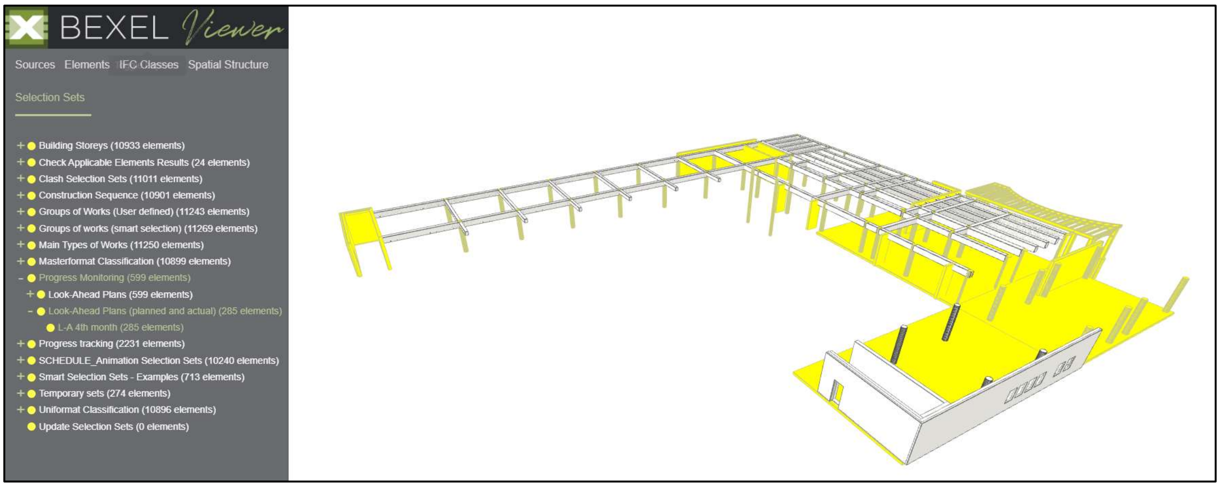


Figure 59 - Actual progress on site during the 4th month. Executed elements selected in yellow

The project manager opens the BCF file shared by the site management team and creates a selection set based on the transferred elements (Figure 60). It is visible that some elements such as beams, part of the external walls, and phase 3 columns were not finished on time and will be transferred to the following month look-ahead plan (month 5).

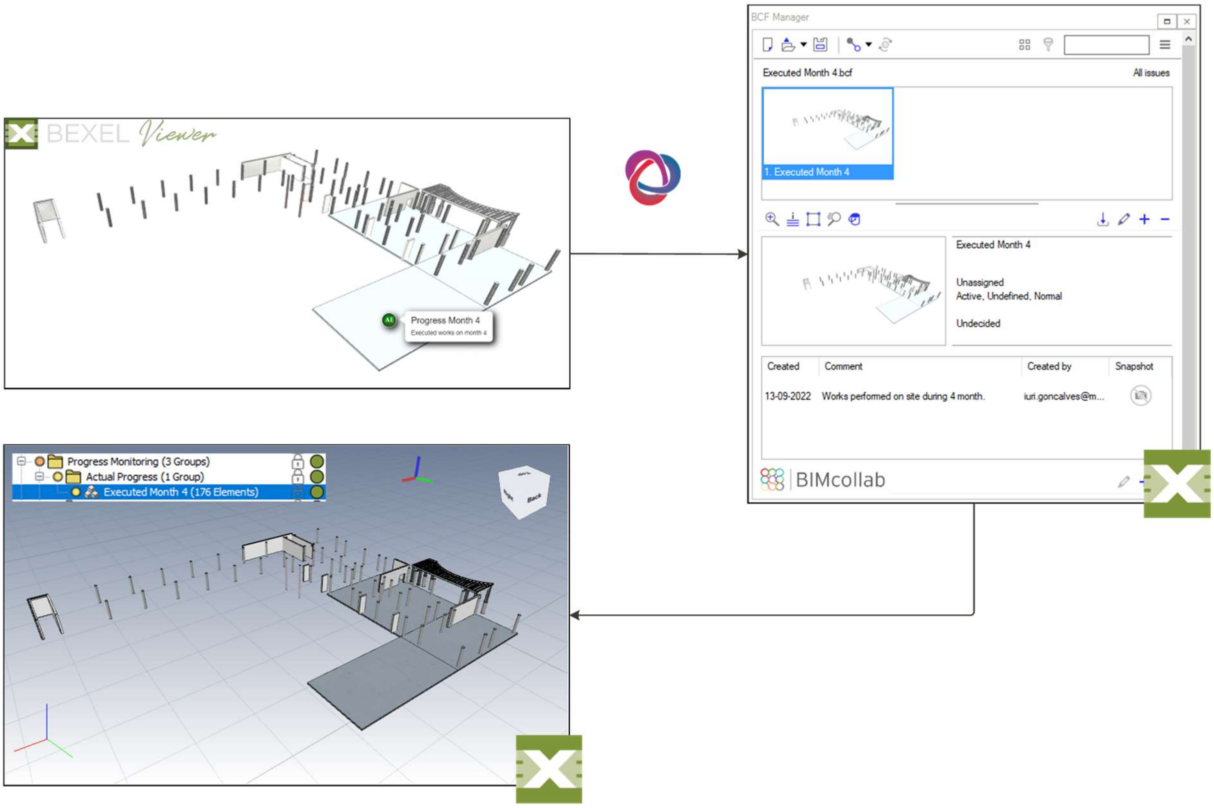


Figure 60 - BCF communication workflow, firstly generated on site and managed by the project manager in *Bexel Manager*.

The next step is to introduce the progress entry in the actual progress schedule and update it. This process is done trough progress mode (*Schedule Progress Editor*) where the project manager can input the information about progress by firstly launching the executed elements selection set for the corresponding month in the *Progress Entry Editor*.

The user specifies the time frame for the progress entry and loads the previously saved selection set of executed works provided by the on site management team. Based on the selected BIM elements from the group the system recognizes all tasks and activities related to these elements that are supposed to be executed within the marked time interval (month 4 in the current case – from April 4th to May 4th). Based on the quantities of these selected elements the system calculates and populates actually executed quantities for each task. For example, if only half of the columns planned for the month were executed, its completion will appear as 50%.

When entering the progress in *Bexel Manager* progress editor the user should be careful when choosing the appropriate option to enter the selection set executed works. The options for the entry of progress are to add *Planned*, *From Selection Sets*, and *Planned from Selection Set*. In this case, since the active schedule is the updated actual schedule, *Planned* option adds the activities and tasks scheduled within the time interval set (according to the schedule itself) and then the user decides which elements were executed and which not. *From Selection Sets*, entries every activity connected to the elements executed grouped in the selection set. *Planned from Selection Set* adds only the activities that were planned according to the active actual schedule from the selection set elements. This means that if the works advanced beyond what was planned according to the actual schedule, for example, these elements and their related activities will not be selected and counted for progress. Hence, a better practice is to add entry *From Selection Sets* to account for possible works performed out of the updated actual schedule plan.

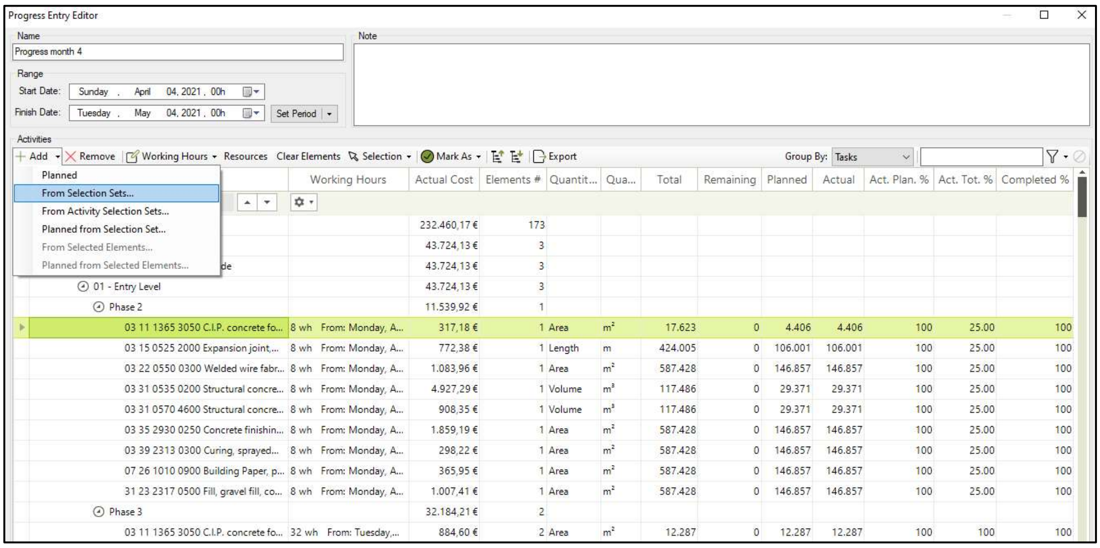


Figure 61 - Progress Entry Editor with tasks and activities performed on month 4.

The progress can be assessed in this table at the level of each activity and resources. Below it is possible to see the different columns representing total quantity of works for each activity.

Activity	Working Hours	Actual Cost	Elements #	Quantit...	Qua...	Total	Remaining	Planned	Actual	Act. Plan. %	Act. Tot. %	Completed %
Enter text to search												
B1010240 Columns - CIP		74.454,37 €	75									
03 11 - C.I.P. concrete forms		22.458,17 €	68									
03 21 - Reinforcing steel		37.184,99 €	69									
01 - Entry Level		37.184,99 €	69									
Phase 1		3.611,97 €	18									
Phase 2		31.165,05 €	39									
Phase 3		2.407,97 €	12									
03 21 1060 0220 Reinforcing steel,...	24 wh From: Wednesd...	2.407,97 €	12	Mass	kg	1017.471	254.368	763.103	763.103	100	75.00	75.00
03 31 - Structural concrete		11.776,68 €	68									
01 - Entry Level		11.776,68 €	68									
Phase 1		3.816,48 €	24									
Phase 2		6.051,97 €	32									
Phase 3		1.908,23 €	12									
03 31 0535 0300 Structural concre...	12 wh From: Monday,...	1.212,91 €	12	Volume	m^3	9.25	2.312	6.937	6.937	100	74.99	75.01
03 31 0570 0600 Structural concre...	12 wh From: Monday,...	695,32 €	12	Volume	m^3	9.25	2.312	6.937	6.937	100	74.99	75.01
03 35 - Concrete finishing		3.034,53 €	68									
01 - Entry Level		3.034,53 €	68									
Phase 1		1.038,60 €	24									
Phase 2		1.476,63 €	32									
Phase 3		519,30 €	12									
03 35 2960 0050 Concrete finishin...	12 wh From: Wednesd...	519,30 €	12	Area	m^2	43.654	10.913	32.74	32.74	100	75.00	75.00

Figure 62 - Columns works activities breakdown.

The importance of having established a work breakdown structures dividing the work activities of each work package becomes even more relevant as the project manager can now manipulate the information on a detailed level taking advantage of the BIM elements and information shared by the construction site team to manage the progress at the activity level.

The site management team has informed that the columns of phase 3 were still not poured and concrete finished. Only the reinforcing steel rebar was assembled along with the formwork. This is introduced in the table by setting the actual quantities as zero (if activities would be completed in only 50% of the columns this could be set in Actual Total %) as shown in Figure 63.

Activities
Add Remove Working Hours Resources Clear Elements Selection Mark As Export Group By: Tasks

Activity	Working Ho...	Actual Cost	Eleme...	Qua...	Qua...	Total	Remaining	Planned	Actual	Act. Plan. %	Act. Tot. %	Completed %
Enter text to search												
B1010240 Columns - CIP		72.026,84 €	75									
03 21 - Reinforcing steel		37.184,99 €	69									
01 - Entry Level		37.184,99 €	69									
Phase 3		2.407,97 €	12									
03 21 1060 0220 Reinforcing steel, in place, colu...	24 wh From:...	2.407,97 €	12	Mass	kg	1017.471	254.368	763.103	763.103	100	75.00	75.00
Phase 2		31.165,05 €	39									
Phase 1		3.611,97 €	18									
03 11 - C.I.P. concrete forms		22.458,17 €	68									
01 - Entry Level		22.458,17 €	68									
Phase 3		4.012,97 €	12									
03 11 1325 1750 C.I.P. concrete forms, column, ro...	24 wh From: T...	4.012,97 €	12	Length	m	61.36	15.34	46.02	46.02	100	75.00	75.00
Phase 2		10.419,28 €	32									
Phase 1		8.025,93 €	24									
03 31 - Structural concrete		9.868,45 €	68									
01 - Entry Level		9.868,45 €	68									
Phase 3		0,00 €	12									
03 31 0570 0600 Structural concrete, placing, colu...	12 wh From:...	0,00 €	12	Volume	m^3	9.25	9.25	6.937	0	0	0	0
03 31 0535 0300 Structural concrete, ready mix, n...	12 wh From:...	0,00 €	12	Volume	m^3	9.25	9.25	6.937	0	0	0	0
Phase 2		6.051,97 €	32									
Phase 1		3.816,48 €	24									
03 35 - Concrete finishing		2.515,23 €	68									
01 - Entry Level		2.515,23 €	68									
Phase 3		0,00 €	12									
03 35 2960 0050 Concrete finishing, walls, burlap...	12 wh From:...	0,00 €	12	Area	m^2	43.654	43.654	32.74	0	0	0	0
Phase 2		1.476,63 €	32									
Phase 1		1.038,60 €	24									

Figure 63 - Columns activities progress entries. Completed % refers to performance of the group of columns belonging to each level phase.

When updating the schedule, it is possible to see the progress for each task in a visual way through the dashed lines on top of the progress bars.

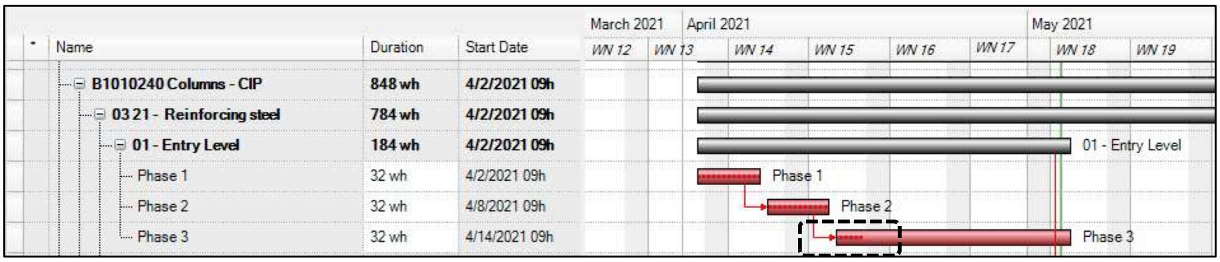


Figure 64 - Schedule and activity's progress bar through visual dashed line.

Regular monthly progress entries – Resources tracking

A lack of productivity noticed at the beam's reinforcement level led to an increase in skilled manpower by the contractor on site during the 5th month and prices of several resources also deviated from the estimated. On the progress editor function of *Bexel* at the activity of reinforcement of beams on the 1st floor the amount of Rodman workers required for the same amount of rebar daily assembled output was increased by 50% (for the same daily output the number of man was raised from 4 to 6). To achieve the schedule plan for beams reinforcement on phase 2 for example, the planned number of workers required to complete the task within the time frame initially set of 4 days (without causing delays) was raised by the contractor from the as-planned 5-6 man to 9, to make ensure the reduction of delays. This information was introduced by means of total number of hours of manpower working on this task from during 4 weekdays (working hours of 8 hours per day).

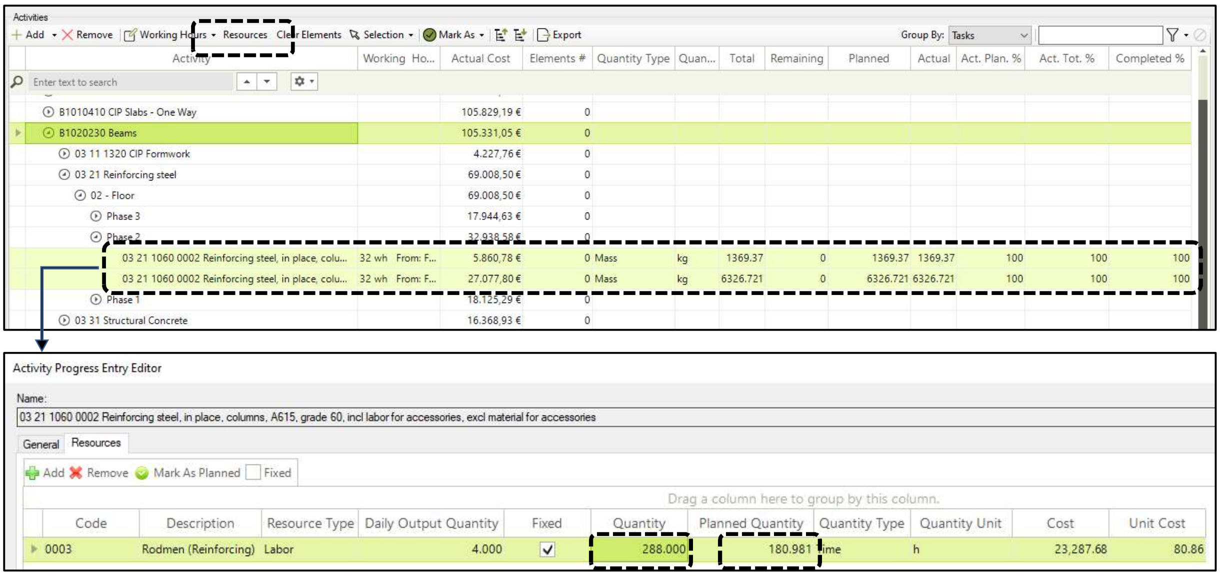
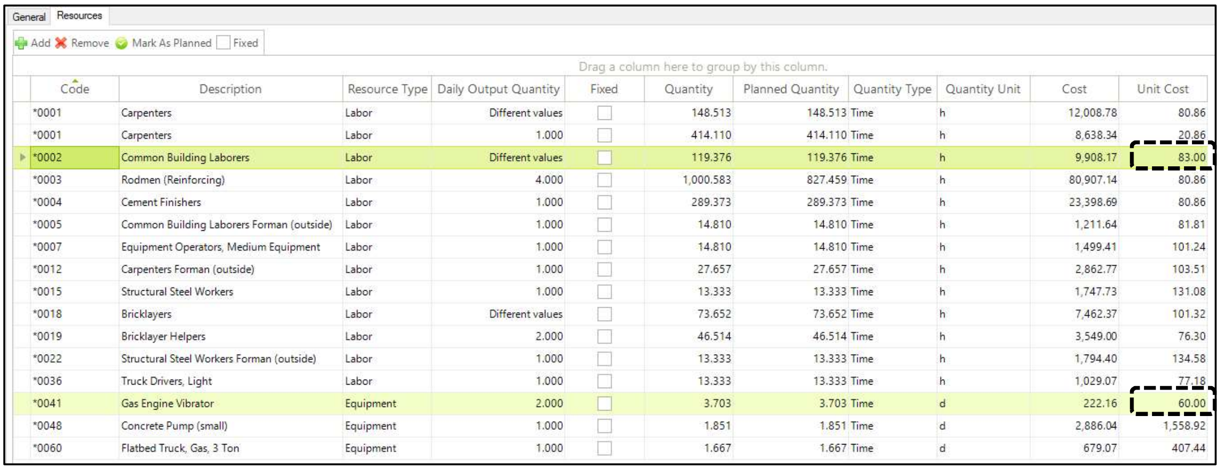


Figure 65 - Activity Progress Entry Editor. Number of hours increase by 50% to reflect the number of workers hired by the contractor to perform this task.

Furthermore, during the same month the unit price of labourers per hour increased by 5% and the price of the gas went up creating extra costs for the project. This information provided by the site management team is introduced through the same previous activity progress editor feature selecting all the works performed during the month and altering unit cost values on the corresponding groups of workers, equipment, or material, in this case: Common Building Labourers and Gas Engine Vibrator.



Code	Description	Resource Type	Daily Output Quantity	Fixed	Quantity	Planned Quantity	Quantity Type	Quantity Unit	Cost	Unit Cost
*0001	Carpenters	Labor	Different values		148.513	148.513	Time	h	12,008.78	80.86
*0001	Carpenters	Labor	1.000		414.110	414.110	Time	h	8,638.34	20.86
*0002	Common Building Laborers	Labor	Different values		119.376	119.376	Time	h	9,908.17	83.00
*0003	Rodmen (Reinforcing)	Labor	4.000		1,000.583	827.459	Time	h	80,907.14	80.86
*0004	Cement Finishers	Labor	1.000		289.373	289.373	Time	h	23,398.69	80.86
*0005	Common Building Laborers Forman (outside)	Labor	1.000		14.810	14.810	Time	h	1,211.64	81.81
*0007	Equipment Operators, Medium Equipment	Labor	1.000		14.810	14.810	Time	h	1,499.41	101.24
*0012	Carpenters Forman (outside)	Labor	1.000		27.657	27.657	Time	h	2,862.77	103.51
*0015	Structural Steel Workers	Labor	1.000		13.333	13.333	Time	h	1,747.73	131.08
*0018	Bricklayers	Labor	Different values		73.652	73.652	Time	h	7,462.37	101.32
*0019	Bricklayer Helpers	Labor	2.000		46.514	46.514	Time	h	3,549.00	76.30
*0022	Structural Steel Workers Forman (outside)	Labor	1.000		13.333	13.333	Time	h	1,794.40	134.58
*0036	Truck Drivers, Light	Labor	1.000		13.333	13.333	Time	h	1,029.07	77.18
*0041	Gas Engine Vibrator	Equipment	2.000		3.703	3.703	Time	d	222.16	60.00
*0048	Concrete Pump (small)	Equipment	1.000		1.851	1.851	Time	d	2,886.04	1,558.92
*0060	Flatbed Truck, Gas, 3 Ton	Equipment	1.000		1.667	1.667	Time	d	679.07	407.44

Figure 66 - Changing unit cost prices according to information from site in terms of expenses and costs on manpower and equipment.

Finally, these changes are considered permanent for the rest of the project and the unit cost of common labourers and number of rodman are changed accordingly, in each month's progress in line with information from site.

Change management – Change of material

Sometimes projects can suffer changes to what was initially predicted to certain activity. One, is the change of material being used for a specific type of constructive element, which can happen for different reasons (supply shortage, saving costs, etc.). During the construction of the roof structure on month 9 (September), the supply chain suffered a shortage of the type of concrete assigned for the roof slab. To not cause extra delays on the building structure the different management teams, consultants and client decided and validated a different type of concrete for the slab.

The roof slab was poured with the initially defined concrete C20 in Phase 1. Phase 2 and Phase 3 suffered a change, and both were decided to be poured with C30 type of concrete. This change is introduced in the corresponding tasks in the schedule by adding a new activity representing the new different material. After adding this new activity, all parameters remain the same (as the pre-defined C20 material activity), and only the cost for the new type of material is updated through the activity unit cost. The cost is defined automatically by the system as "other" type of cost instead of "material" (Figure 67). *Bexel* does not allow the user to change the type of cost directly in the task editor, leading in this case to a lack of detail if an analysis regarding materials cost is required. However, it is still useful to control total cost of the activity and quantities of work performed, and ultimately to assess deviations from planned, project performance indicators.

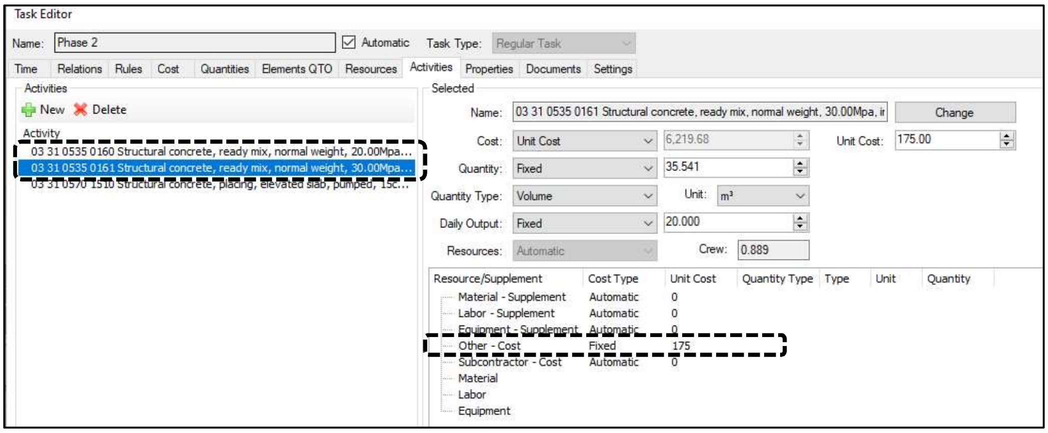


Figure 67 - Roof slab phase 2 task editor. Adding new activity representing the new material (C30) along with its unit cost and total quantity (previous activity quantity with C20 is set to zero).

It is important that the change is properly classified and displayed during the construction monitoring, so that the impact and consequence of the change is properly displayed. In is illustrated the roof slab concrete pouring task report, showing the quantities produced on each month. The green and orange activities represent the different types of concrete ready mix used on site, before (Phase 1) and after (Phase 2 and 3) the decision of changing the type of material to be used. The third activity represents the actual pouring process of the slab, comprising the other resources, equipment, and manpower.

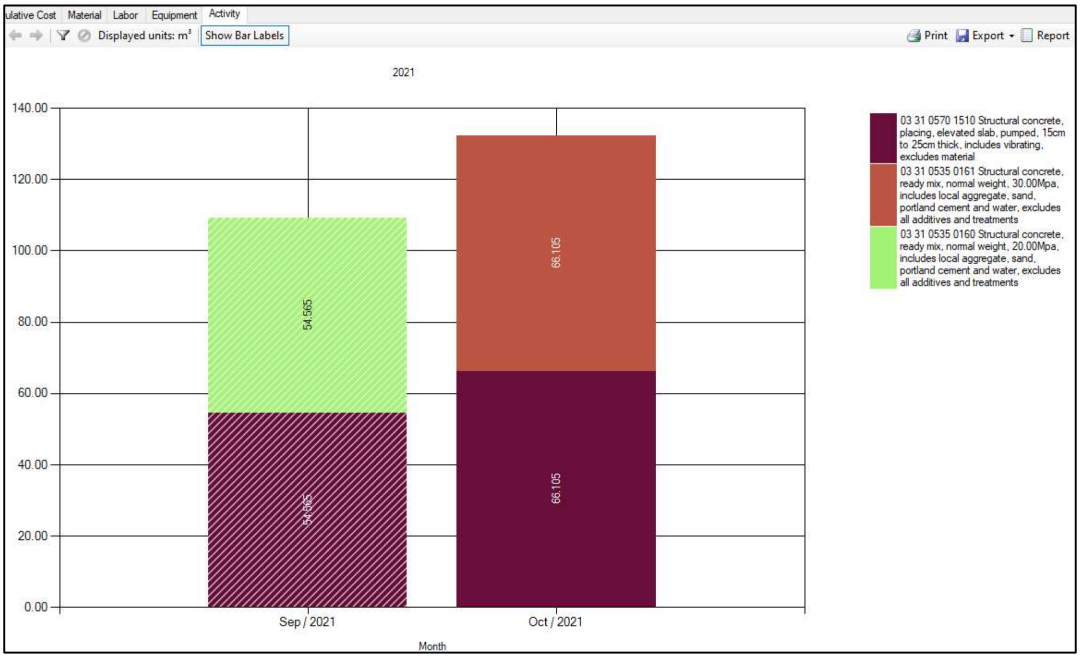


Figure 68 - Roof task activities report. Total quantities divided by month and type of activity.

It is important to notice that this procedure is not updating the BIM model itself in terms of materials. In case these changes are to be adopted and further implemented in the final as-built model, necessary action and appropriate changes need to be done through an ongoing model update process (or before handover to the client) by the contractor. The information in *Bexel* can be used to aid in this task.

Change management – Design changes

Some of the major changes that can occur during the construction progress are due to design changes, which can represent significant differences in quantities. To take this into account, the updated BIM model with the most recent design modifications done in the authoring tool, must be sensibly entered into the software. If changes are done to the original building or if there are extra elements to be added, the federated model in *Bexel* can be updated and the software will match and analyse missing, modified and new elements. After the update, the building quantities, cost breakdown versions and schedules are also automatically updated in supervised way ensuring the efficiency and consistency of the process. To illustrate these changes procedure, it is assumed that during construction phase of the case study, new elements were added to design, more specifically to the structure. A cover on the side entrance of the building on the ground floor is displayed below.

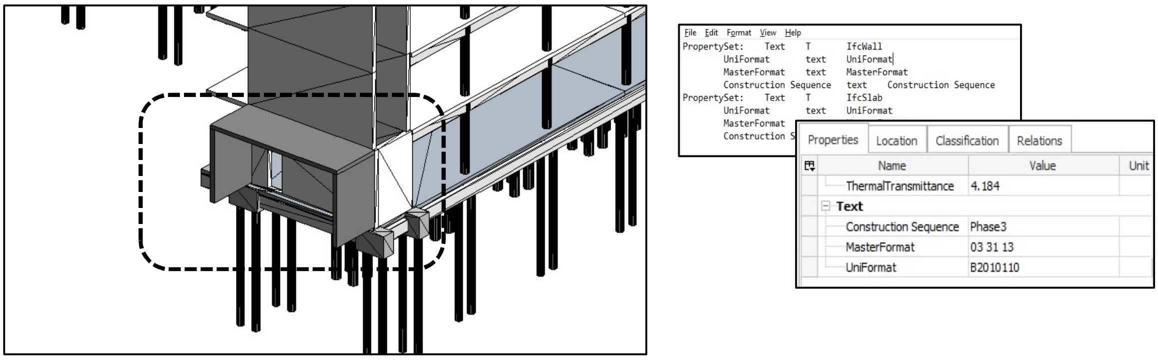


Figure 69 - Design change in authoring software

In the process of exporting these design changes to IFC format from the authoring tool, besides quantities, essential properties associated with the new elements were mapped to ensure the efficiency of the integration in *Bexel* breakdown structures and schedule (e.g., Construction Sequence or UniFormat). Once imported and added to the cost breakdown structure, by creating a new cost version in Bexel is possible to see the difference in the price and furthermore its integration in the schedule. The user has the freedom to decide how to manage and display these changes. In this case, a different cost item for control of work variations was created as shown in Figure 70 to better control this type of construction events. Since this design change does not represent critical activities that might hinder the continuity of other works, no delays are reflected on the plan.

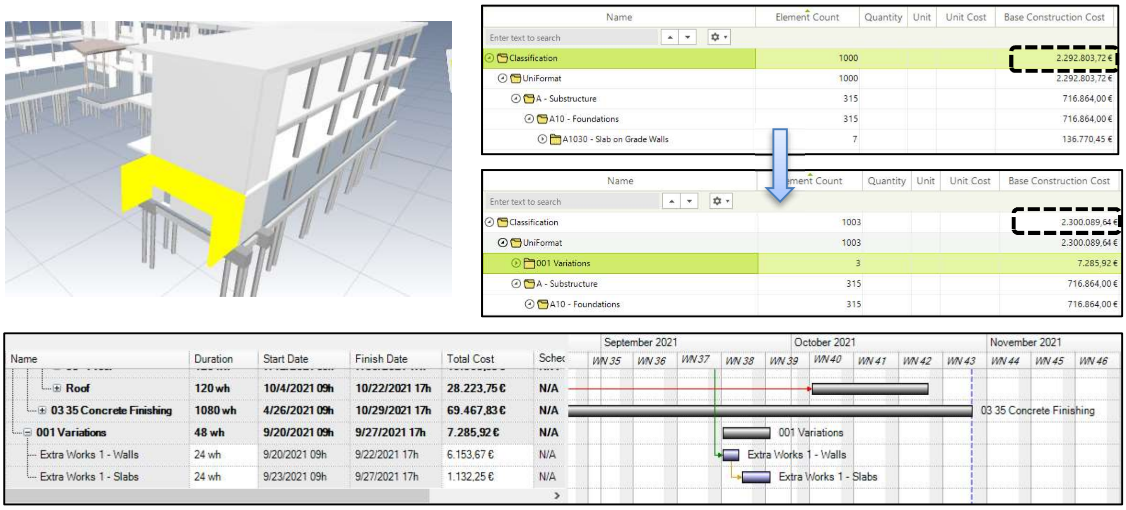


Figure 70 - Design changes control workflow. On the top right are shown the cost versions before and after integration of new design and related works. Below the schedule reflecting the update.

New out of planned tasks – Adding site control supervision

At certain points during the construction progress might be required to have new different tasks that were not initially planned. In this case, after the contractor decided to add a team dedicated only for field supervision, in order to control all the works on site and help on the progress tracking and maintaining works productivity on a regular daily basis.

To contemplate this extra item in the progress management system, it needs to be first added to the project cost breakdown structure, taking into consideration the classification system.

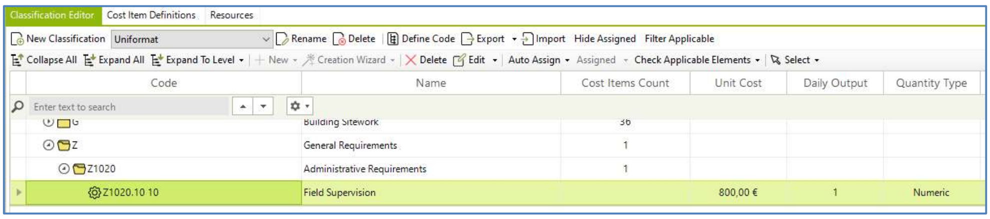


Figure 71 - Introducing new cost item in CBS.

This procedure is followed by integrating this item in the updated schedule through a process of assigning the cost item of *Field Supervision* to the CBS, defining its unitary cost (considered as a site supervisor fixed cost per hour) and creating a new schedule task linked to this information. It is important to indicate in the system that this cost item is not connected to any BIM element, and that the task quantities output of work will be represented and measured by number of working hours, since it embodies an ongoing activity independent of constructive objects that will be continuous until the end of the project.

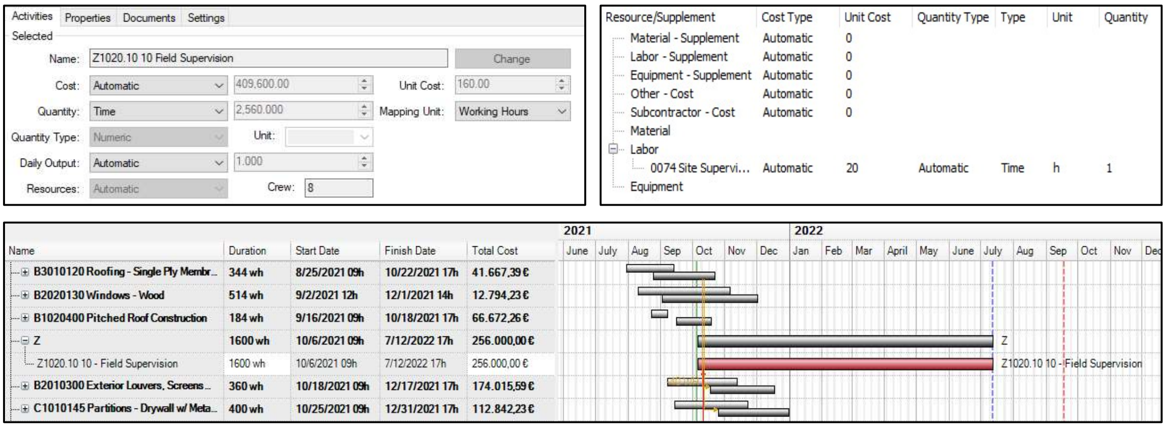


Figure 72 - Adding Field Supervision work item to the schedule.

Adding the field supervision is expected to be a positive factor to the project leveraging of productivity and efficiency of the works on site, reducing several activities duration and consequently time spent by operators performing their jobs and further costs. This information is entered through the progress entries on each month at the level of activities and resources actual duration.

4.2.3 Schedule Optimization

During the project development on site the delays and changes to different activities require a schedule optimization to avoid idle times and to ensure the continuity of the construction works.

To support this task, by analysing the line of balance, it becomes possible to better understand the flow of works and make required adjustments to starting times of activities as well as durations.

Additionally, by assessing the project tasks report and its analytics the project manager gets an insight of cumulative costs, detailed information on number of labourers (daily), as well as the quantities of scheduled work forecast based on the different activities output. This data provides the necessary basis for optimization of manpower, which plays a critical role on the project performance.

For the current case study, after entering the progress of month 10 (October 2021), the amount of specific type of labourers that were irregularly spread throughout the construction phase was levelled and optimized. By reviewed the labourer task report it is possible to observe high peaks of number of glaziers on site during some periods and uneven placement of electricians (Figure 73).

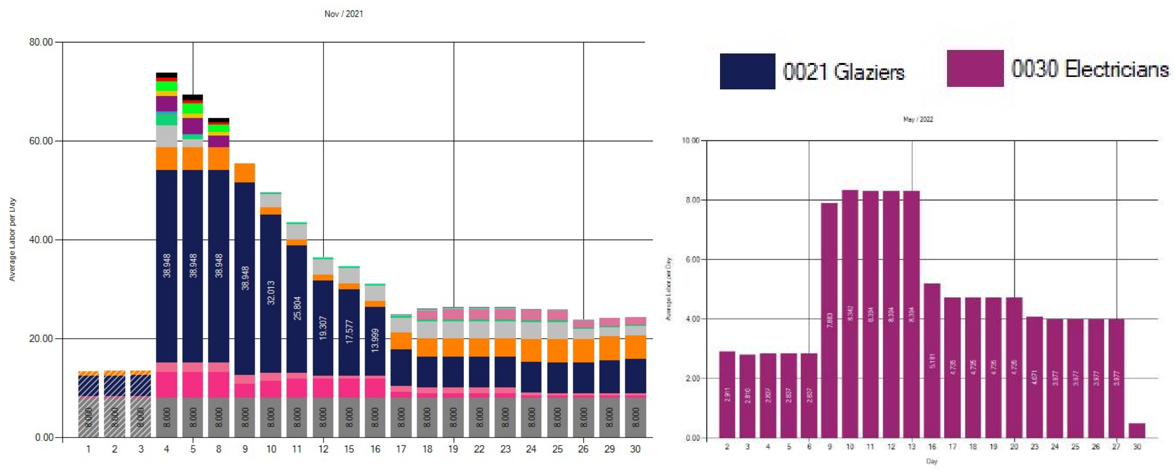


Figure 73 - Distribution of number of Glaziers (on the left in blue) throughout November 2021 and Electricians (on the right) during the month of May 2022.

The difference in the number of labourers from one week to the other is unsustainable and unrealistic. Thus, adjustments were done by firstly extend durations of the related tasks (curtain walls and electrical wiring, etc) and then by using the levelling feature of *Bexel* in process that tries to achieve a more sustainable and regular amount of workforce during these activities works. It is important to note that by minimizing and regularizing the labourer allocation, there still might be a need to stretch the related tasks since the duration of the different works depend on the amount of manpower and their productivity. The option taken was of extending tasks where required, but the PM might opt to delay. This can happen if for example two different tasks that require the same type of labourer are occurring at the same time.

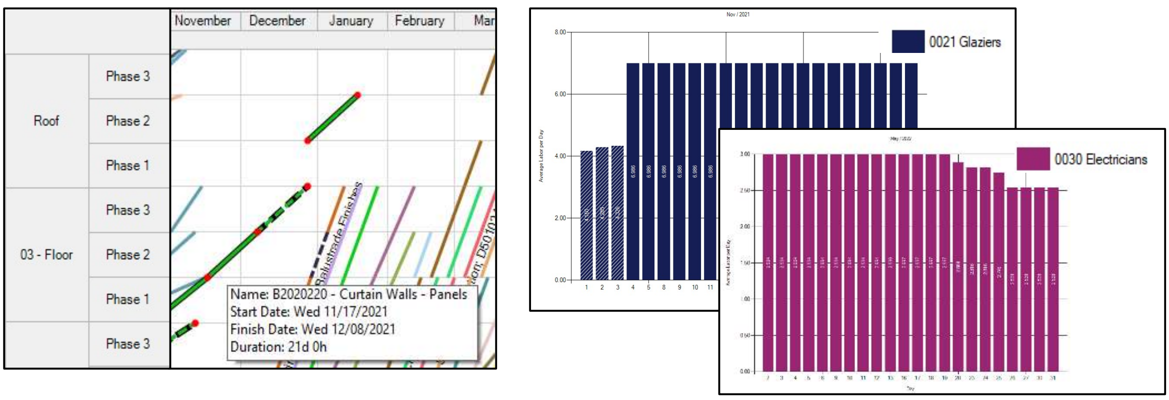


Figure 74 – LOB and schedule optimization by extending tasks and levelling resources allocation.

4.2.4 Communication

Throughout the entire process of construction progress monitoring, beyond capturing, store and manage data, the goal is to convert it to a form that is readable and appropriate to all stakeholders enabling them to take informed decisions through key data and furthermore, to realistically assess the performance and state of the project. To make this possible, the communication of the progress information is organized according to what is more important to each stakeholder through tables, charts or BIM visualizations.

The output of the ongoing process of progress management used to communicate the relevant process information are progress reports, audit trails, and monthly payment certificates.

Power BI is later used to display relevant and meaningful information, which after processing data and creating different charts, these can be employed in the form of reports for the different stakeholders through templates.

Monthly Payment Certificates

The progress management process makes use of several tools and procedures to ensure the good performance of construction works by assessing it through different indicators and making important decisions along its course. On another hand, this analysis is also important to the client and contractor (subcontractors) since the outputs from this process are the basis for valuations and monthly payment certificates.

In construction, interim certificates are normally adopted, meaning that the payments from the client to the contractor are done on a monthly basis, according to the percentage of works completed and their values, representing a partial part of the project total payment. The valuation of works done by the contractor (validated by the site management and site supervision) is confirmed and agreed with the project management and the client, leading to the generation of the monthly payment certificate.

Bexel Manager has the capacity of generate payment certificates in an automated manner from the input of progress information as mentioned earlier. By defining the time interval and exporting the related data, the software generates an Excel spreadsheet with pivot tables organizing the construction activities as in the cost breakdown structure, with all quantities, percentages of completion and associated costs updated. The pivot table can be further modified and customized, and is divided by contracted quantities and budget, certified accumulated payment until the certification period, the quantities and prices of the actual works executed during the certification month (amount to be paid), and finally what is currently certified what is missing until finishing.

Description	CONTR. UNIT COST	CONTR. QTY	CONTRACTED PRICE	PREV. CERTIFIED (ACCUMULATION) QTY	PREV. CERTIFIED (ACCUMULATION) PRICE	EXEC. IN CERTIFICATION PERIOD QTY	EXEC. IN CERTIFICATION PERIOD PRIC	TOTAL CERT. TO DATE QTY	TOTAL CERT.TO DATE PRICE	BALANCE TO FIN. QTY	BALANCE TO FIN. PRICE
⊟Uniformat											
⊞G-Building Sitework	$261.21	443367.55	$961,564.54	636.64	$12,002.04	0.00	$0.00	636.64	$12,002.04	442730.91	$949,562.51
⊟A-Substructure											
⊟A10-Foundations											
⊞A1010-Standard Foundations	$130.34	12384.79	$531,499.82	12384.79	$531,499.82	0.00	$0.00	12384.79	$531,499.82	0.00	$0.00
⊞A1020-Special Foundations	$44.30	3541.16	$45,996.43	3541.16	$45,996.43	0.00	$0.00	3541.16	$45,996.43	0.00	$0.00
⊟A1030-Slab on Grade Walls											
31 23 2317 0500 Fill, gravel fill, compacted, under floor slabs, 10cm c	$6.86	1740.54	$11,939.76	1184.11	$8,122.74	556.43	$3,817.02	1740.54	$11,939.76	0.00	$0.00
07 26 1010 0900 Building Paper, polyethylene vapor barrier, standar	$2.49	1740.54	$4,337.22	1184.11	$2,950.66	556.43	$1,386.57	1740.54	$4,337.22	0.00	$0.00
03 39 2313 0300 Curing, sprayed membrane compound (m²)	$2.03	1740.54	$3,534.44	1184.11	$2,404.52	556.43	$1,129.93	1740.54	$3,534.44	0.00	$0.00
03 35 2930 0250 Concrete finishing, floors, monolithic, machine trov	$12.66	1740.54	$22,034.97	1184.11	$14,990.61	556.43	$7,044.36	1740.54	$22,034.97	0.00	$0.00
03 31 0570 4600 Structural concrete, placing, slab on grade, direct ch	$30.93	348.11	$10,765.76	236.82	$7,324.06	111.29	$3,441.71	348.11	$10,765.76	0.00	$0.00
03 31 0535 0200 Structural concrete, ready mix, normal weight, 23.3	$167.76	348.11	$58,397.91	236.82	$39,728.69	111.29	$18,669.22	348.11	$58,397.91	0.00	$0.00
03 22 0550 0300 Welded wire fabric, sheets, 6 x 6 - W2.9 x W2.9 (6 x	$7.38	1740.54	$12,846.99	1184.11	$8,739.94	556.43	$4,107.05	1740.54	$12,846.99	0.00	$0.00
03 15 0525 2000 Expansion joint, premolded, bituminous fiber, 1.3cr	$7.29	1256.32	$9,154.18	854.69	$6,227.68	401.63	$2,926.50	1256.32	$9,154.18	0.00	$0.00
03 11 1365 3050 C.I.P. concrete forms, slab on grade, edge, wood, 17	$71.99	52.22	$3,759.21	35.52	$2,557.43	16.69	$1,201.78	52.22	$3,759.21	0.00	$0.00
⊟B-Shell											
⊟B10-Superstructure											
⊟B1010-Floor Construction											
03 39 2313 0300 Curing, sprayed membrane compound (m²)	$2.03	3078.30	$6,512.70	0.00	$0.00	0.00	$0.00	0.00	$0.00	3078.30	$6,512.70
03 35 2930 0250 Concrete finishing, floors, monolithic, machine trov	$12.66	3078.30	$38,970.80	0.00	$0.00	0.00	$0.00	0.00	$0.00	3078.30	$38,970.80
03 21 1060 0003 Reinforcing steel, in place, walls, #3 to #7, A615, gra	$2.20	12599.77	$27,779.37	655.27	$1,444.71	2787.23	$6,145.15	3442.50	$7,589.86	9157.27	$20,189.51
03 21 1060 0220 Reinforcing steel, in place, columns, A615, grade 60,	$3.16	12106.18	$38,201.07	381.55	$1,203.99	3731.90	$11,776.03	4113.46	$12,980.02	7992.72	$25,221.05
⊟C3010-Wall Finishes											
09 91 1320 3600 Paints & Coatings, interior, on plaster or drywall, br	$17.35	8572.52	$148,717.34	0.00	$0.00	0.00	$0.00	0.00	$0.00	8572.52	$148,717.34
⊟Z-General Requirements											
⊟Z1020-Administrative Requirements											
⊟											
Z1020.10 10 Field Supervision	$160.00	1520.00	$243,200.00	0.00	$0.00	0.00	$0.00	0.00	$0.00	1520.00	$243,200.00
⊞E-Equipment & Furnishings	$339.20	100.00	$20,830.29	0.00	$0.00	0.00	$0.00	0.00	$0.00	100.00	$20,830.29
⊞	$175.00	66.11	$11,568.38	0.00	$0.00	0.00	$0.00	0.00	$0.00	66.11	$11,568.38
Grand Total	$268.24	938363.41	$8,229,195.01	25389.84	$690,336.93	18909.76	$240,796.97	44299.60	$931,133.91	894063.80	$7,298,061.11

Figure 75 - Interim certificate. Monthly payment certificate for project's month 4 (April).

Progress Report

As previously shown, task report is possible to compare the baseline and actual schedules in detail and analyse the difference in cash flow dynamics, cumulative cost information, labour and material needs, giving a useful track information of every important aspect for progress management. Furthermore, to communicate with other involved parties, progress reports can be generated, with the same figures from the progress entries generated in *Bexel*. It exports progress data to *Excel* creating customized pivot tables where percentages of actual vs planned monthly progress, as well as activities' balance of total quantity performed are displayed and arranged according to tasks and activities (associated used resources are also identified by activity). On a different section, resources actual and planned allocation related to the progress in the defined time interval are broken down and actual total percentages and quantities (hours, days) per resource type are presented.

Type	In Range	Visible
Activity	TRUE	TRUE
Equipment Resource		
Labor Resource		
Task		

Type	Code	Name	Start Date	Finish Date	Planned Q	Actual Qua	Total Quantity	Quantity Ty	Quan	% Plan	% Actu	% Actu	% To
Task		Project Dissertation : V06	04. January 2021. 09:00	18. August 2022. 10:00									
Task		A Foundations	08. January 2021. 09:00	09. April 2021. 17:00									
Task		A1030200 Structural Slab on Grade	25. March 2021. 09:00	09. April 2021. 17:00									
Task		01 - Entry Level	25. March 2021. 09:00	09. April 2021. 17:00									
Task		Phase 2	31. March 2021. 09:00	05. April 2021. 17:00									
Activity	03 11 1365 3050	03 11 1365 3050 C.I.P. concrete forms, slab o	31. March 2021. 09:00	05. April 2021. 17:00		4.406	17.623	Area	m²		25.00		100.00
Labor Resource	0001	0001 Carpenters	31. March 2021. 09:00	05. April 2021. 17:00		2.616	10.466	Time	h		25.00		100.00
Labor Resource	0002	0002 Common Building Laborers	31. March 2021. 09:00	05. April 2021. 17:00		0.872	3.489	Time	h		25.00		100.00
Activity	03 15 0525 2000	03 15 0525 2000 Expansion joint, premolded	31. March 2021. 09:00	05. April 2021. 17:00		106.001	424.005	Length	m		25.00		100.00
Labor Resource	0001	0001 Carpenters	31. March 2021. 09:00	05. April 2021. 17:00		7.419	29.677	Time	h		25.00		100.00
Activity	03 22 0550 0300	03 22 0550 0300 Welded wire fabric, sheets,	31. March 2021. 09:00	05. April 2021. 17:00		146.857	587.428	Area	m²		25.00		100.00
Labor Resource	0003	0003 Rodmen (Reinforcing)	31. March 2021. 09:00	05. April 2021. 17:00		8.721	34.886	Time	h		25.00		100.00
Activity	03 31 0535 0200	03 31 0535 0200 Structural concrete, ready m	31. March 2021. 09:00	05. April 2021. 17:00		29.371	117.486	Volume	m³		25.00		100.00
Activity	03 31 0570 4600	03 31 0570 4600 Structural concrete, placing,	31. March 2021. 09:00	05. April 2021. 17:00		29.371	117.486	Volume	m³		25.00		100.00
Labor Resource	0004	0004 Cement Finishers	31. March 2021. 09:00	05. April 2021. 17:00		1.863	7.450	Time	h		25.00		100.00
Labor Resource	0002	0002 Common Building Laborers	31. March 2021. 09:00	05. April 2021. 17:00		7.450	29.802	Time	h		25.00		100.00
Labor Resource	0005	0005 Common Building Laborers Forman (ou	31. March 2021. 09:00	05. April 2021. 17:00		1.863	7.450	Time	h		25.00		100.00
Equipment Resour	0041	0041 Gas Engine Vibrator	31. March 2021. 09:00	05. April 2021. 17:00		0.466	1.863	Time	d		25.00		100.00
Activity	03 35 2930 0250	03 35 2930 0250 Concrete finishing, floors, m	31. March 2021. 09:00	05. April 2021. 17:00		146.857	587.428	Area	m²		25.00		100.00
Labor Resource	0004	0004 Cement Finishers	31. March 2021. 09:00	05. April 2021. 17:00		22.993	91.971	Time	h		25.00		100.00

Figure 76 - Progress report for the project's month 4 (April).

Alternatively, this report can be used for helpful progress information input by the site team. If it is required to communicate percentages of completeness of activities that are still not yet finished in a manual way, the spreadsheet can be used to insert this information and to be further assessed by the project management while processing progress. It is also possible to import it directly in the software system as progress entry. However, this is a less recommended method since some important information regarding resources allocation for example, becomes inaccurate (resources distributed throughout the certification period and not related to start and end dates).

As mentioned earlier the software also provides task reports that can be visualized in software interface. Below is displayed the report of cumulative costs for the whole project and comparison between actual and baseline schedule.

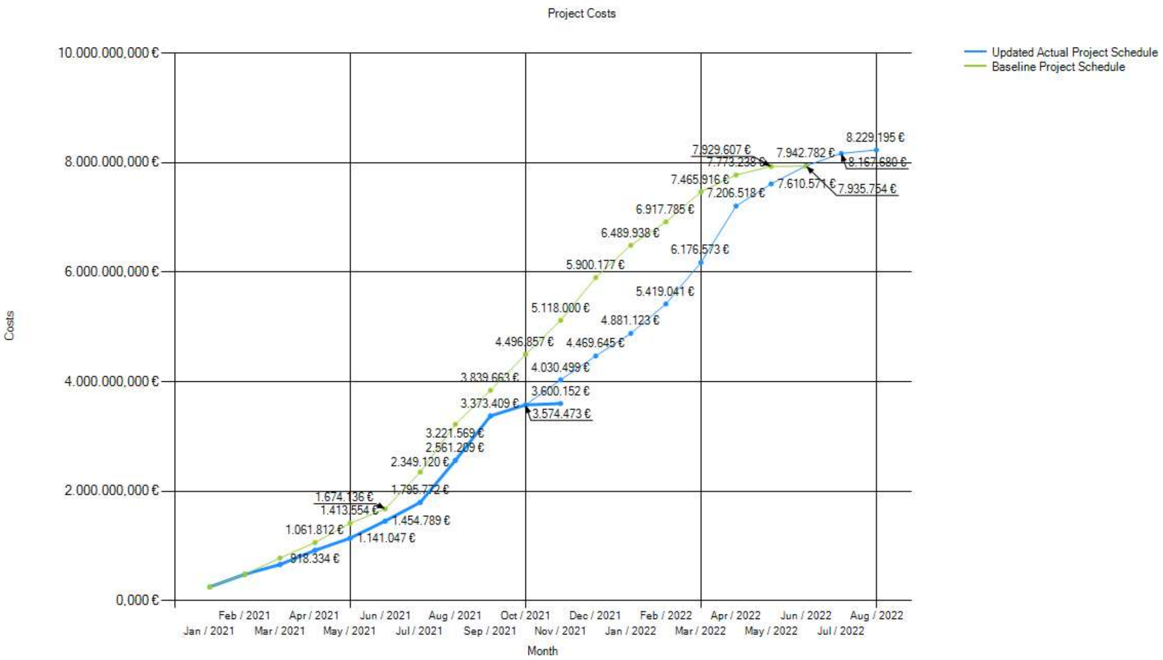


Figure 77 - Bexel Manager Cumulative Cost Report. After October the blue line represents the forecast of actual costs from the updated actual project schedule.

Audit Trail

All changes and procedures occurred during construction are registered through the audit trail. This chronological process provides historical record on the project progress that becomes useful for management and tracing of events and information flow. The implementation of an audit trail brings several advantages to the progress management in different ways by keeping record of the responsible and accountable actors for any occurrence, giving background for reconstruction of events to detect and reduce future problems or registering financial transactions.

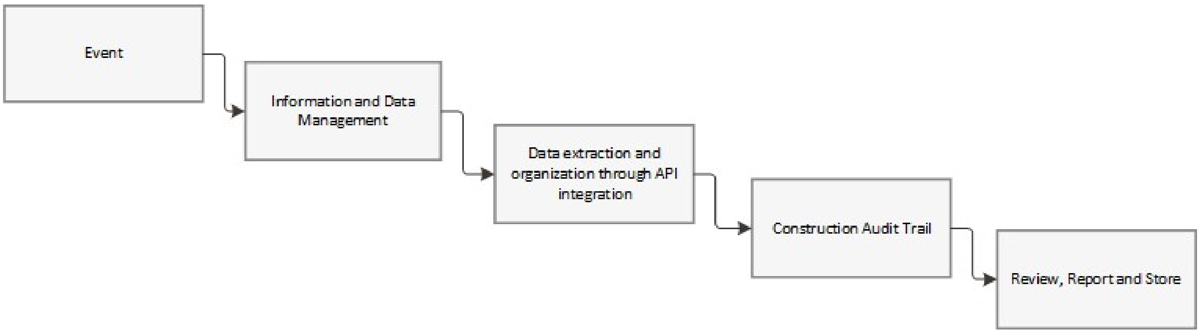


Figure 78 - Audit Trail update workflow.

The proposed workflow to achieve a continuous update of the audit trail operates through several steps. As shown in previous sections, when any relevant event for progress management occurs, information and data are gathered and integrated in the process system in different ways. The information management regarding delays, design changes, progress entries or payment certificates during construction is critical and generates data that can be used to keep records of each of these events. To compile the audit trail, the required data is retrieved and organized through API generating reports by type of events in a chronological manner. The output of this process is further reviewed and stored for future access and analysis.

An example of this workflow can be the process of registering delays input directly on the schedule and report it on an audit trail. In case this delay is introduced on a specific activity for example, changing its duration, starting and finishing dates, these changes to the activity can be retrieved and added to the audit trail spreadsheet through the integrated *Bexel's* API console by running scripts capable of identify data modification. Additionally, the date of the change and the responsible user are recorded. The audit trail is finally updated, reviewed, and stored.

4.2.5 Earned Value Analysis

The ongoing assessment of the project performance as well as communication with clients and stakeholders can be done by using Power BI. This is powerful tool makes use of dashboards with graphical representations and indicators to enable not only the efficient assessment of the project performance through data comparison, Earned Value Analysis and KPIs, but also the effective communication between the different stakeholders enhancing decision making.

One of the relevant Power BI views for analysis is the progress control of each work package. The progress of works can also be seen in a general way. The illustration below shows a chart with the distribution of each type of work actual cost per month, which is further broken down in the table and compared against the Earned Value and Planned Cost. The actual cost and earned value correspond to the situation on the moment of the last project entry, in this case, October (month 10).

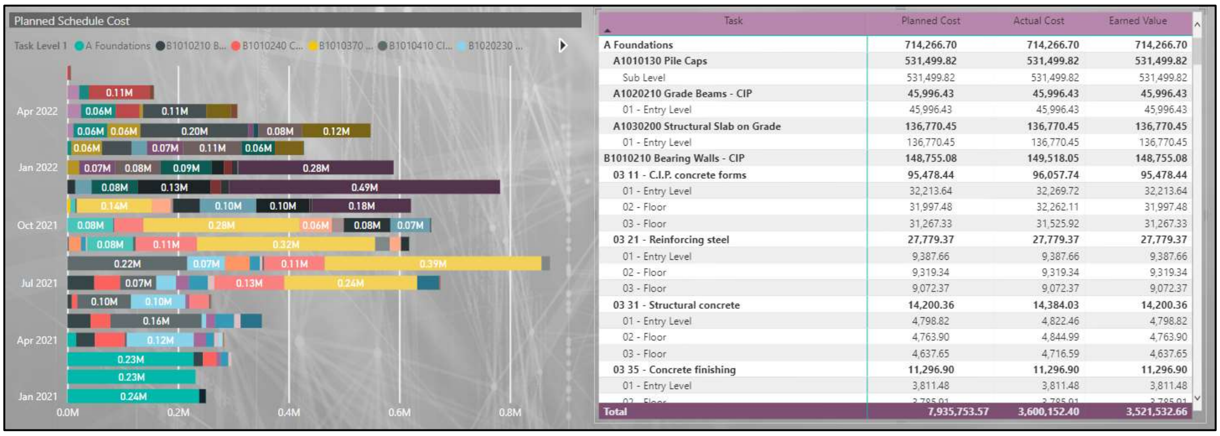


Figure 79 - Construction progress through costs with Power BI using *Bexel* template.

The Earned Value Analysis graphics and information provides important insight on the current situation of the project and performed works. Key performance indicators are calculated supporting assessment of the project delay and cost overruns. These performance indicators and analysis can be done at the tasks or work packages level, also by floor, taking the analysis to a more detailed level when required.

In the example of the study here developed, the Earned Value Analysis by the moment of last progress entry reflects a considerable delay of works (schedule performance index – 0.77). In terms of actual total cost, the current deviation from Earned Value is slight and that can be seen by comparing the charts on the top left of Figure 80, or assessing each work package actual cost versus its planned cost (earned value) associated to the amount of work produced up to date (cost performance index). The forecast predicts an extra total cost of project at around 290.000€.

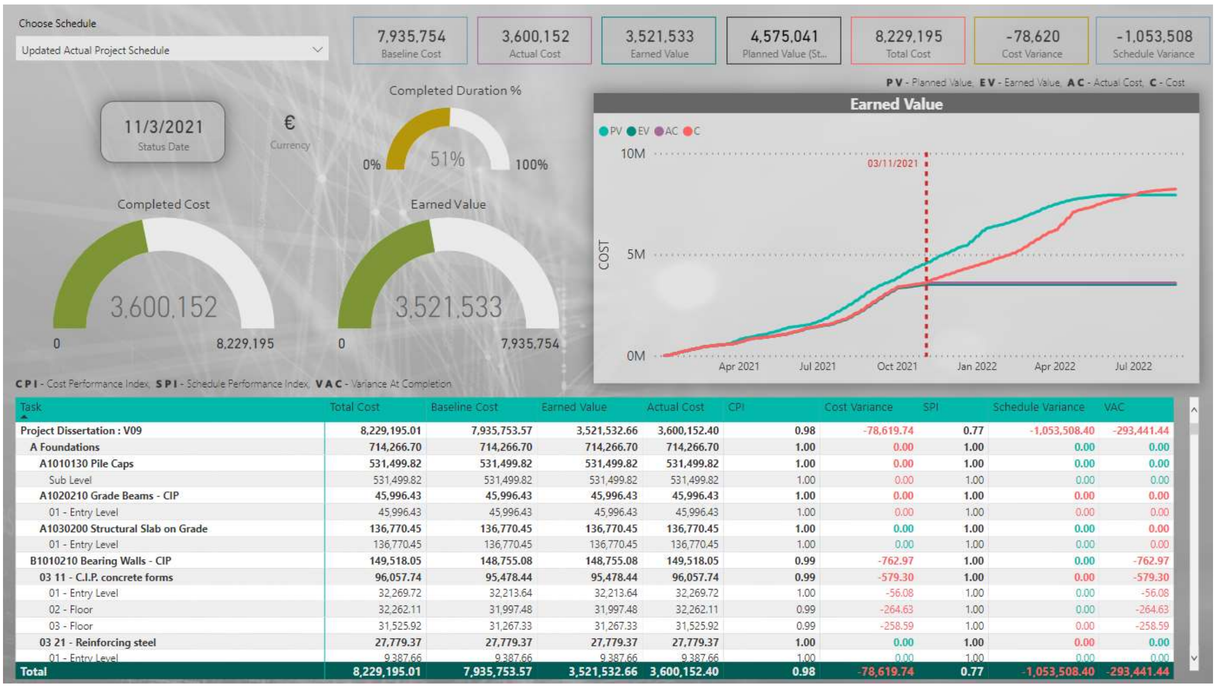


Figure 80 - Earned Value Analysis in Power BI.

As an example of controlling the project at the level of different work packages, the picture below illustrates the curtain wall panels case, which is a still ongoing job. Its performance so far can be displayed by key performance indicators, and this graphical information is filtered just by selecting the task in the table. By analysing information, it can be observed that the only time the curtain walls progress was ahead of schedule was by the end of August (SPI – 1.12) and becoming delayed right after during the month of September. Furthermore, Power BI enables also the control and analysis of resources which can provide great insight on manpower costs and productivity and material use performance.

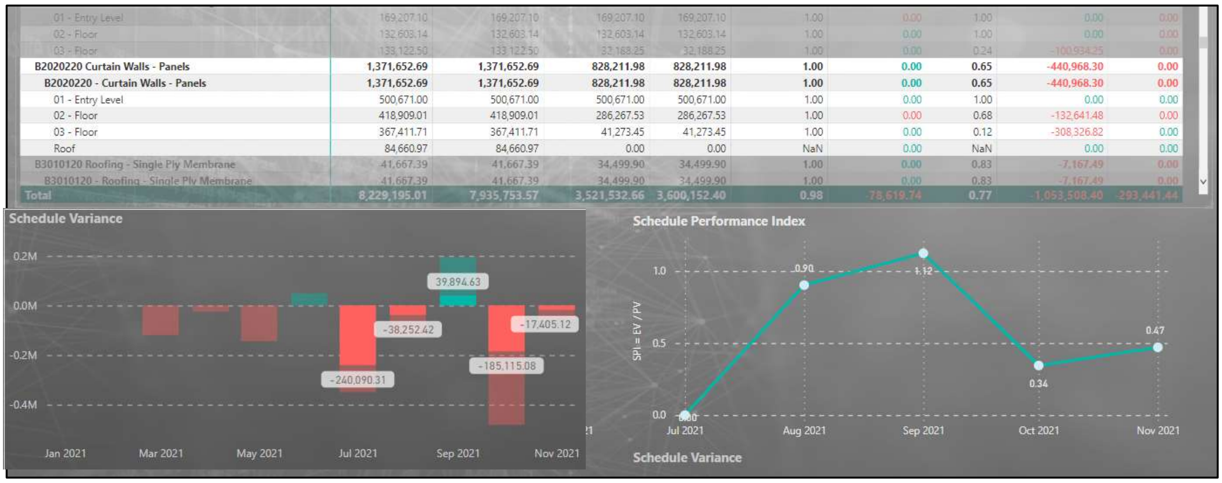


Figure 81 - Curtain Walls Panels schedule performance index reflecting delays.

5 CONCLUSIONS

5.1 Discussion and Conclusions

Although information technology is developing at a high pace, the construction sector is still lagging behind when it comes to take advantage of these innovative and disruptive advancements. However, the digitalization of the construction industry is not even throughout all its phases. The conceptual and design stages of construction projects are largely digitized, making use of BIM to improve process and leverage productivity and collaboration amongst all involved parties. The construction phase on another hand is still behind and a lot of traditional methods and processes are still in place. To overcome this issue, BIM can be the catalyst of change by combination with innovative methods and other technologies to improve construction project management processes and aspects such as integration, collaboration, and communication.

Progress management is a fundamental component of construction project management. This study focused on conducting a research and assessing advanced frameworks and workflows for the progress management of construction projects identifying innovative methods and tools that can support its implementation contributing for the innovation of the industry.

The construction process output is a physical asset which cannot be computerized, stored and accessed in a shared database. Thereby, traditional unproductive and error-prone ways of collecting information and data from site, require innovation towards more efficient methods to help keeping track of progress. The disruption of data acquisition, through the rapid growth of imaging technologies and techniques can improve significantly automated progress monitoring. These methods were reviewed relatively to its implementation on construction sites. After the identification of the main possible technologies and techniques, an analysis on their advantages, limitations and compatibility was conducted. A conclusion was reached that the methods used for the data acquisition process must be carefully selected according to the type of project and its environment. Additionally, the process of data acquisition must be thoroughly planned, and data quality requirements must be in place to enhance its value.

The conducted research explored also different approaches used for data processing and further comparison between as-built and as-planned BIM models. Scan-to-BIM and Scan-vs-BIM are the main techniques to transform data acquired on site in the form of point clouds, to BIM models representing the as-built construction. These approaches successful implementation require the identification of information requirements – identifying required building elements and non-geometric attributes, as well as the level of detail of the point cloud – to further determine the scan data quality and optimize its acquisition.

- Scan-to-BIM is related to the modelling of required elements through the application of trained and knowledge-based machine learning algorithms on point clouds, automating the generation of the as-built BIM model. The research found that there is still a lack of automation on generating the BIM model directly from the point cloud.
- On another hand, Scan-vs-BIM is an object-based detection technique that compares the acquired point cloud data with the as-planned BIM model, and based on proximity metrics between the two, it generates an as-built BIM model consisting of the objects automatically recognized and uniquely identified in the as-planned model. A limitation of this method can be the threshold for proximity. A restrictive criteria might lead to the non-identification and recognition of elements that are actually present in the scene.

Furthermore, the topics of progress quantification and visualization were examined, revealing its importance not only for accurate measurement of works, but also for communicating the progress with the different involved parties. Reducing the amount of time for decision making and explanatory descriptive tasks is of upmost importance for the stakeholders. The integration of BIM, apart from improving the construction progress quantification, it also enables the construction simulation, providing visuals of the progress during the whole construction phase.

A framework for progress management application in construction projects was created and applied to an illustrative case study. This case study made use of the *Bexel Manager* software to further manage different types of progress events during the construction phase, from design changes to monthly progress entries, to delayed activities and resources tracking.

The case study was illustrative and required assumptions were made throughout. The development of the project case study revealed the following:

- An efficient work breakdown structure is essential for the accurate control of the project progress. Depending on the scale of the project and the level of detail and information required for control, the further the WBS should be broken down and associated with specific costs, enabling the precise management of progress at the activities level. This level of information is required in the case that the manager pretends to control, for example, the deviation of the cost of a specific labourer on a specific activity.
- The model organization into groups is of great importance to control different parts of the construction progress of the building, enabling changes to initial plan and schedule or even performance control at this level. Besides that, required properties for this model breakdowns are essential and can be assigned to elements through the authoring software before exported to IFC, or directly in *Bexel* through the designated add-in.

- Introducing changes in *Bexel* benefits from its open BIM environment where BCF file formats and IFC models from other sources can be introduced leveraging a better communication between site and project management and interoperability with other software. In this case to test this interoperable workflow, *Bexel Viewer* application was tested with positive results.
- The progress management entries and changes can be introduced in different ways. The better practices are shown, and important notes are made throughout the chapter. It is important to mention that the software does not assign costs automatically to activities without BIM elements and this requires a special attention by the user.
- Communication of the results of progress management are done through progress reports, monthly payment certificates and audit trails. The two first ones are easily generated in the software, being exported to pivot tables allowing further customization. The workflow proposed to generate audit trails takes advantage of the *Bexel* single source of truth system enabling the information and data retrieval of almost any item, property or action taken within the software.
- Finally, the Power BI feature offers the possibility of displaying the Earned Value Analysis in a clear and interactive way, letting the user select specific tasks or work packages and see associated progress performance through key performance indicators, giving insight on cost deviations and also regarding current and future delays.

5.2 Summary and Contribution

Nowadays, construction progress is still monitored in a traditional way reviewing the project status through paper or digital documentation with estimations and schedules and in some individual cases, when the construction progress documentation by contractors allows it, through the aid of software such as *Oracle Primavera* linking assets or cost items to the schedule, increasing somewhat the automation of the monitoring process based on the baseline schedule and tender estimate. However, these methods are unprecise and inaccurate facilitating the possibility for human errors due to the lack of related and integrated data with spatial resolution and representation. Thus, this study proposes an advanced construction progress management leveraging Building Information Modelling and integrated construction schedule and cost data through the use of *Bexel Manager*, empowering the continuous management of progress performance. Furthermore, the framework proposed, supported by the development of a case study, attempts to simplify, and improve the progress control process by making it efficient and providing accurate and up-to-date high-quality data to determine the current state of the construction project, enabling reasoned and effective real-time decision making.

5.3 Future Research

As future research it is proposed the implementation of the framework on a real case scenario and evaluate its capability in terms of efficiency, cutting progress management process times and costs associated to these procedures and assess the promptness and accuracy of decision making and Earned Value Analysis. Furthermore, adding subcontractors to the process would also reflect its robustness.

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